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Two-Channel Electrotactile Stimulation for Sensory Feedback of Fingers of Prosthesis*

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***Abstract*— Electrotactile stimulation has been used to provide sensory information of forearm prosthesis to users. Although conventional sensory feedback method, where one electrode expresses sensory information of only one finger, could provide force information of three fingers by using three electrodes, it showed less cognitive accuracy when more than two electrodes were stimulated simultaneously compared to individual stimulation. To improve the cognitive accuracy, we presented a sensory feedback method called two-channel electrotactile stimulation for the thumb, index and middle fingers using only two electrodes. The force information of the index and middle fingers was delivered into two electrodes, respectively, by intermittent stimulation. The information of the thumb was delivered to the user by inserting additional offset pulses onto the channel of the index finger based on an assumption that the force of thumb is proportional to the sum of the forces of the index and middle fingers. The presence of offset pulses in the channel indicates the binary state of thumb if it contacts with an object or not. We conducted two psychophysical experiments where healthy subjects classified the binary states of each finger and identified intensity from two-channel stimuli. The cognitive accuracies for intensity identification were 78.8% and 62.2% for the intermittent stimulation and conventional method, respectively, and accuracy for classifying the fingers was 93.1% for every combination of the three fingers. The results demonstrated that the proposed two-channel electrotactile stimulation could be an attractive method to express the information of fingers of prosthesis with high accuracy.**

I. INTRODUCTION

Technological progress in commercial forearm prostheses enables upper limb amputees to recover their activity function in daily living. Nevertheless, due to the absence of sensory feedback in the prosthesis, users still have difficulty in conducting an elaborate work and establishing embodiment to the prosthesis. To provide the users with sensory function, researchers have been investigating sensory feedback techniques to substitute sensory information of a prosthesis for electrotactile stimulation on residual limb.

Depending on the number of sensory variables to be deliverd, one or more electrodes can be chosen for electrotactile stimulations. One-channel electrotactile stimulation which uses only one electrode was used to feedback an average grasping force or the level of hand opening of prostheses in virtual grasping simulation [1], [2], [3]. It increased the performance of grasping force control and the cognitive accuracy for identification of hand configurations compared to the case of no sensory feedback. Also, subjects were able to discriminate the stiffness of given objects only relying on sensory feedback without visual feedback. Even though it was possible to interact with the environment using information from one-channel sensory feedback, the detailed information from each finger of a prosthesis could not be obtained.

To provide the state of individual fingers, multi-channel electrotactile stimulation in which each electrode represents each finger was suggested [4], [5]. Geng and Jensen [4] instructed subjects to mentally associate three electrodes on the forearm with the thumb, index, and middle fingers, respectively, and investigated the cognitive accuracy for identification of location and pulse number of three-channel electrotactile stimulation. Zhang $et\ al.$ [5] investigated five-channel case on the upper arm in which stimulation with three levels of intensity and two types of feeling was given. In multi-channel sensory feedback, one finger-one electrode mapping made subjects easily associate the stimulus of each channel with sensory information of each finger of a prosthesis.

However, all attempts above used more than three electrodes and showed poor cognitive accuracy for the case of simultaneous stimulation of more than two channels compared to the case in which only one channel was stimulated. Also, when more than two electrodes were stimulated, they did not make differences between intensities of each channel. It means that multiple information of the intensity which an array of electrodes can have was not fully utilized by setting them to the same level. In this case the users can not perceive the forces of the fingers independently even when a prosthetic hand generates forces of each finger with different levels, failing to deliver the detailed information. However, if stimuli were given with different intensities at each channel to provide multi-channel information independently, it would show more poor cognitive accuracy due to the complexity of given stimuli.

The reason why three-channel was typically chosen for sensory feedback was to express at least the state of the thumb, index and middle fingers which play important roles in grasping compared to the ring and little fingers. However, three-channel stimulation did not show satisfactory performance of recognition and independency between channels seemed hard to be achieved. This is because not only the amount of information but also the difficulty of cognition increases as the number of channel increases. Mental load to users possibly caused by the difficult cognition would make the multi-channel method hard to be applied to sensory

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feedback for a prosthesis.

In this paper, we propose a sensory feedback method using two-channel electrotactile stimulation for the information of the thumb, index, and middle fingers. By using two electrodes rather than three, we intended to lower the mental effort and raise the cognitive accuracy for the stimulation. Two stimulation methods, one for encoding three fingers into two channels and the other for independency between the channels which has not been tried in three-channel, are introduced. The forces of the fingers in grasping which prosthesis users mostly want to know were chosen for feedback information. The proposed method was evaluated by two psychophysical tests.

II. METHODS

A. Assumption

Thumb is usually oriented to the opposite of the index and middle fingers to support them when we grasp an object using these three fingers. In this case we can assume that thumb force (F_{thumb}) is approximately equal to the sum of the forces of the index (F_{index}) and middle finger (F_{middle}).

$$F_{thumb} \approx F_{index} + F_{middle}. \tag{1}$$

Because the force of thumb which is coupled with that of the index and middle fingers can be approximated by them, only contact state is enough for sensory feedback of thumb. Thumb force can be considered as a binary on/off value, i.e., contact with an object or not, instead of continuous one. Two independent information from the index and middle fingers are expressed by two channels, respectively, and the on/off value of thumb can be added subsidiarily to the index channel without additional channel. The ring and little fingers which do not function independently [6] are not considered for feedback.

B. Two-channel Intermittent Stimulation with Offset Pulses

For independent feedback of the forces of the index and middle fingers, users have to be able to recognize intensities of the stimuli of each channel. However, when two channels are stimulated simultaneously, masking effect (i.e., strong stimulus of one channel masks relatively weak stimulus of the other) makes it difficult to recognize them correctly. To reduce the masking effect, 'two-channel intermittent stimulation' can be used (Fig. 1 (a)). Unlike simultaneous stimulation [7] where square pulses are presented continuously in both channels at the same time, stimuli alternates between the channels. Thus, stimulation time of the two channels is divided and the masking effect is expected to be reduced. There are five parameters for two-channel intermittent stimulation: frequency, pulse width, amplitude, burst period and burst duration. Frequency determines time interval between two consecutive pulses. We used 100Hz for frequency to evoke pressure-like sensation [8]. The intensity of the pressure is proportionally changed by the pulse width of each square pulses. Because pressure and force have

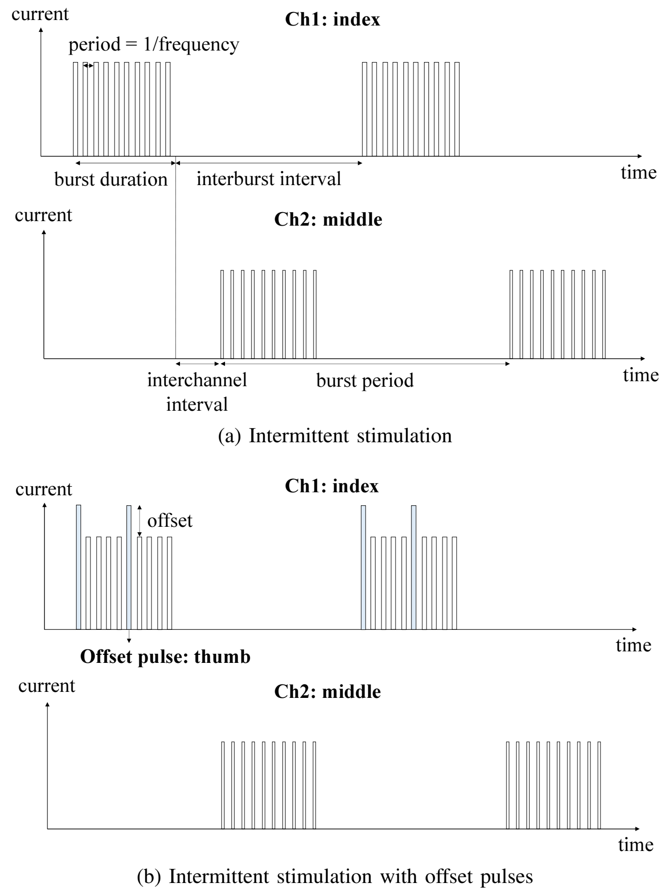


Fig. 1. Waveforms of stimulating current in two channels. (a) Intermittent stimulation with 100Hz frequency evokes pressure-like sensation in each channel. Grasping forces of the index and middle fingers are expressed by the evoked pressures whose intensities are proportional to pulse widths of each channel. (b) Offset pulses which have larger amplitude than others by offset add tapping along with underlying pressure from 100Hz pulses. Contact of thumb can be encoded by addition of the offset pulses, that is the tapping.

the same modality, pressure is proper to represent grasping forces of each finger of a prosthesis.

Burst period is stimulation period in a channel. It should be upper bounded because longer burst period leads to slower update of information in a channel in which the change of grasping force cannot be delivered to users effectively. To avoid aliasing of feedback information, the upper bound of burst period was set as follows. First, we assumed that the change rate of grasping force is less than 1Hz when controlled by amputees myoelectrically judging from the specification of one commercial myoelectric prosthesis [9]. To capture the maximum and minimum values of the grasping forces, at least 2Hz feedback was necessary and the maximum value of burst period was set to 0.5s.

Burst duration was set to less than or equal to a half of burst period not to overlap stimulation time of the two channels. Even if stimulation of the two channels is not overlapped, slight masking may happen by the residual sensation right after stimulation is over, that lasts to the beginning of the stimulation in the other channel. Interchannel interval between stimuli of the two channels would reduce that possibility by delaying upcoming stimulus until the residual sensation disappears. To determine parameter values, a pilot test was conducted as follows. For burst period of 0.1s, 0.2s, 0.3s, 0.4s and 0.5s, five representative values below the upper bound, the ratio of burst duration to interchannel interval was set to 1:1 or 2:1. Among total ten parameter sets, one set which had the best cognitive accuracy for two-channel stimuli was found. The test was conducted in the same way with experiment 1 which will be explained in the next section. As a result of the test for two subjects, 0.4s burst period and 1:1 ratio of burst duration to interchannel interval were chosen. Intermittent stimulation was proposed as a method to slow down adaptation to electrotactile stimulation in the past [10]. By applying it to two-channel stimulation for division of stimulation time of the two channels, we expect to not only slow down the adaptation but also reduce the masking effect as well.

By inserting offset pulses which have larger amplitude and lower frequency among 100Hz pulses, two different frequencies can be encoded in one electrode. We found that pressure-like sensation from the 100Hz pulses and tapping from the offset pulses were evoked simultaneously, when stimulus with the waveform of Fig. 1 (b) were given to subjects. Because the added tapping did not change the modality of pressure heavily, simple addition (or not) of offset pulses (without intensity modulation) was able to express a binary on/off value easily regardless of underlying pressure. The pulse width modulations of 100Hz pulses of each channel generate proportional pressures which represent the forces of the index and middle fingers, and the addition of the offset pulses can express the on/off value of thumb's contact simultaneously. Offset was set to 2mA to discriminate tapping from underlying pressure. Two offset pulses were added in a burst duration of intermittent stimulation to make tapping be perceived clearly. It feels like two taps along with underlying pressure.

In the case of thumb's contact only, just offset pulses generate tapping and pressures disappear due to zero pulse widths of 100Hz pulses. Offset pulses actually function as a virtual channel which delivers the on/off value without addition of a physical channel (electrode). This makes it possible to express sensory information with three variables using only two electrodes.

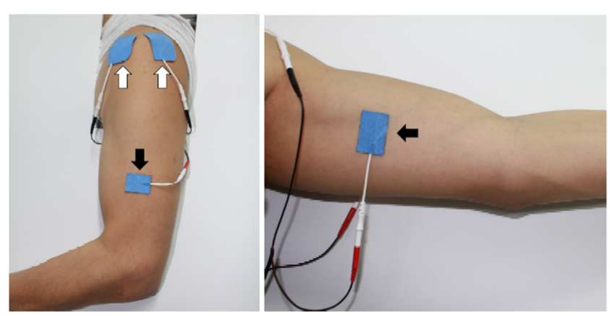
C. Experimental Protocol

Two psychophysical experiments were conducted to investigate performances of the proposed stimulation methods, intermittent stimulation and offset pulses. Ten healthy subjects (age 21-30, mean 24.6±2.9, 10 males) participated in the experiments. The subjects had no visible skin diseases in the upper arm and no history of any neurological and psycological disorders. All subjects were given explanation about the procedure of the experiments and consented to it. This experimental protocol was approved by the local Ethics Committee of KAIST where the experiments took place.

The subjects sit at ease with left arm on a cushion. Two pairs of active and reference electrodes (self-adhesive with hydro-gel, skin contact size: 20x30mm/33x48mm, square shape, Ag/Carbon film) were used (Fig. 2). The active electrode of channel 1 for the index finger was placed on radial nerve of left arm between the brachialis and triceps muscle, about 10cm from the elbow. That of channel 2 for the middle finger was placed on ulnar nerve of left arm between the bicep and triceps muscle, about 10cm from the elbow. The reason why these locations were selected was that we found a clear sensation was elicited and muscle twitches occurred rarely than others through the pilot test. These locations were found by palpation. Two reference electrodes were placed on acromion which was relatively insensitive to electrical stimuli in order for subjects to concentrate on the sensation evoked at the active electrodes. Relative position of reference electrodes is not important because it does not contribute to the sensation. The skin was prepared by moisturizing with a alcohol swab to decrease skin impedance. A custom-made electrical stimulator was used.

Prior to the experiments, sensation (ST) and pain threshold (PT) to the monophasic square pulses were determined for each channel by varying pulse widths. The frequency and amplitude were set to 100Hz and 4.5mA respectively, and the pulse width was increased in equidistant steps (10μs) while the subjects verbally indacated the two points when he/she felt a slight sensation (ST) and an uncomfortable sensation (PT). In each of the two experiments, a learning was carried out before assessment of the performance. All pattern used in each experiment was presented to the subjects up to five times in random order until the subjects said correct answers in two consecutive or five repetitions were over for each pattern. The subjects took one minute rest after the learning and 5 minutes rest between experiments as well as every time when subjects felt fatigue or residual sensation. Total experiments took one to one and a half hour depending on the subjects. Two experiments are described as follows.

1) Experiment 1. Recognition of Intensity Patterns of Two-channel Stimuli: The purpose of experiment 1 was to investigate how well the subjects perceived two-channel stimuli during intermittent (Fig. 1 (a)) and simultaneous (as a comparative experiment) stimulation of mononphasic square pulses. In both stimulation methods, nominal values



(a) (b)

Fig. 2. Electrodes placement: (a) active electrode for the index finger (black arrow) and reference electrodes for the index and middle finger (white arrow). (b) active electrode for the middle finger (black arrow).

of frequency and amplitude were set to 100Hz and 4.5mA for both channels. Four levels (zero, weak, medium, strong) of intensity for each channel were combined to a total of 15 different stimuli except the case of zero stimulus in both channels. The pulse widths for each level were set to zero = 0, weak = ST+0.2*(PT-ST), medium = ST+0.5*(PT-ST) and strong = ST+0.8*(PT-ST). Because cognitive characteristics to electrical stimuli of each channel are different due to difference of electrodes placement, the amplitudes and pulse widths of each channel were adjusted slightly until the identical levels of stimuli given in both channels were perceived as similar levels of intensity to each other. The subjects conducted two sessions for intermittent and simultaneous stimulation, respectively once. A half of subjects did intermittent stimulation first, and the other half in reverse order to decrease bias from the fatigue or learning effect. For each session, there were total 75 trials (15 patterns X 5 repetitions) in random order. The subjects was instructed to push the switch which stop the stimulation when he found out the answer and an experimenter recorded it.

2) Experiment 2. Recognition of the binary states of each channel: The purpose of experiment 2 was to investigate how well the subjects perceive the presence of the offset pulses (Fig. 1 (b)) regardless of the stimuli of channel 1 and 2. Intermittent stimulation with two levels of intensity (zero, medium) for each channel was used to express the on/off of channel 1 and 2, i.e., contact states of the index and middle fingers, and offset pulses were added as a virtual channel to express the on/off of thumb's contact. Among eight combinations from the on/off of three channels, seven patterns except all off were used in the experiment. There were total 70 trials (7 patterns X 10 repetitions) in random order. The subjects did the same thing as experiment 1 when he found out the answer and an experimenter recorded it.

D. Data Analysis

Accuracy, i.e., the percent of correctly recognized stimuli, was the performance metric for all experiment. The recognition was considered successful if the states of all channel including offset pulses were correctly recognized by subjects. For experiment 1, the accuracy for each pattern, six patterns of one-channel stimuli, nine patterns of two-channel stimuli, and fifteen patterns of total stimuli were calculated from the result of intermittent and simultaneous stimulation. For experiment 2, the accuracy for total patterns and the marginal accuracy, i.e., the accuracy for one channel regardless of the other channel were calculated.

A paired two-tailed t-test was applied to compare accuracies of intermittent stimulation to simultaneous stimulation from experiment 1. A one-way ANOVA and a post-hoc test using Tukey's multiple comparison was applied in order to compare the marginal accuracies of each channel from experiment 2.

III. RESULTS

Fig. 3 describes the result of experiment 1. Total accuracies were 62.2±11.2% and 78.8±9.5% for simultaneous and intermittent stimulation. For the one-channel stimuli, accuracies were 76.3±11.8% and 86.3±7.3% for simultaneous and intermittent stimulation. For the two-channel stimuli, accuracies were 52.9±14.5% and 73.8±12.6% for simultaneous and intermittent stimulation. Statistically significant differences between simultaneous and intermittent stimulation were found in all accuracy (total accuracy and accuracy for the two-channel stimuli: $p < 0.001$ and accuracy for the one-channel stimuli: $p < 0.05$). The accuracies for each intensity pattern sorted by the stronger intensity of the two channels were given in Table I and II for simultaneous and intermittent stimulation, respectively. Abbreviations for intensity patterns are as follows (o: zero, w: weak, m: medium, s: strong stimulus, w.m: weak in channel 1 and medium in channel 2). The average accuracies for 'Stronger': weak, medium and strong were 77.3%, 60.8%, and 57.1% for simultaneous stimulation, and 92.0%, 77.2%, and 74.6% for intermittent stimulation.

Fig. 4 describes the result of experiment 2. Total accuracy for 7 patterns was 93.1±4.8% and the marginal accuracies for channel 1, channel 2 and offset pulses as a virtual channel were 100%, 97.4±2.4%, and 94.4±4.5%. A statistically significant difference ($F(2, 27) = 8.98$, $p < 0.05$) was found only between channel 1 and offset pulses ($p < 0.001$).

IV. DISCUSSION

A. Independent Perception of Two-channel Information

Multi-channel sensory feedback using more than three electrodes has been regarded as one solution to deliver multi-variable information such as grasping forces of the fingers of a prosthesis. However, few works have tried to stimulate multi channels independently, i.e., with different intensities of each channel, possibly due to poor cognitive accuracy for three stimuli with different intensities. Sensory feedback of more than three independent variables seems hard to be achieved and would impose high mental load to users due

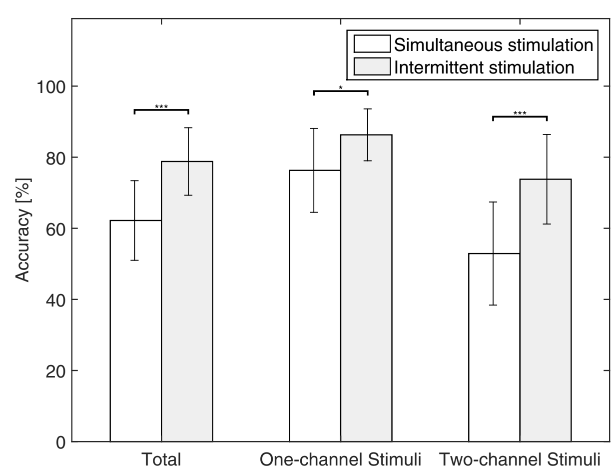


Fig. 3. Accuracy for intensity patterns of simultaneous and intermittent stimulation. The three categories in horizontal axis show total accuracy and the accuracies for one-channel and two-channel stimuli, respectively. Asterisk legend: * $p < 0.05$, *** $p < 0.001$.

TABLE I

ACCURACY FOR INTENSITY PATTERNS OF SIMULTANEOUS STIMULATION SORTED BY STRONGER INTENSITY OF TWO CHANNELS

	Intensity pattern														
	Stronger: weak			Stronger: medium					Stronger: strong						
	w.o	o.w	w.w	m.o	o.m	m.w	w.m	m.m	s.o	o.s	s.w	s.m	w.s	m.s	s.s
Accuracy [%]	92	90	50	66	84	40	60	54	60	66	50	58	60	54	52
(Standard deviation)	(14)	(14)	(33)	(21)	(13)	(31)	(16)	(25)	(42)	(28)	(27)	(20)	(27)	(30)	(25)
Average [%]	77.3			60.8					57.1						

TABLE II

ACCURACY FOR INTENSITY PATTERNS OF INTERMITTENT STIMULATION SORTED BY STRONGER INTENSITY OF TWO CHANNELS

	Intensity pattern														
	Stronger: weak			Stronger: medium					Stronger: strong						
	w.o	o.w	w.w	m.o	o.m	m.w	w.m	m.m	s.o	o.s	s.w	s.m	w.s	m.s	s.s
Accuracy [%]	92	98	86	78	84	68	82	74	90	78	56	78	74	62	84
(Standard deviation)	(10)	(6)	(19)	(18)	(23)	(25)	(26)	(21)	(19)	(30)	(25)	(11)	(19)	(24)	(18)
Average [%]	92.0			77.2					74.6						

to the complexity of information. Independency between feedback channels was also not easy for two-channel stimulation because of masking effect. We found there existed the masking effect in which the average accuracy for intensity patterns of two-channel stimuli decreased significantly as the intensity of one of two channels increased, especially for simultaneous stimulation (Table I) which is usually used in many studies . Strong stimulus of one channel seemed to hinder the recognition of relatively weak stimulus of the other. On the other hand, intermittent stimulation was rather robust to the masking effect (Table II), where the average accuracy for 'Stronger: strong' was similar to that for 'Stronger: weak' of simultaneous stimulation. This result implies that division of stimulation time in intermittent stimulation actually has an effect on reducing the masking effect between channels. A statistically significant difference in accuracy for two-channel stimuli between simultaneous

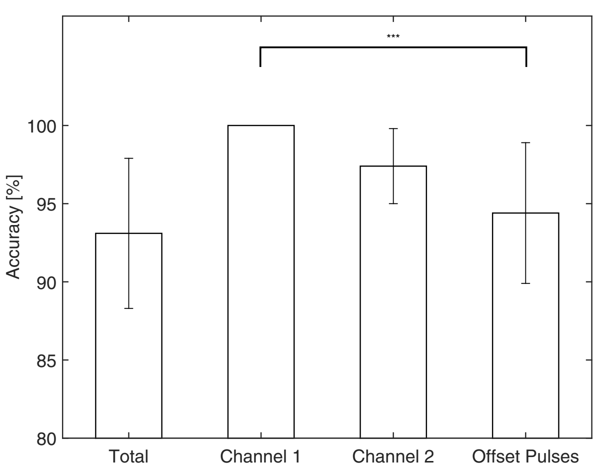


Fig. 4. Accuracy for the binary states of each channel. The four categories in horizontal axis show total accuracy and the marginal accuracies for channel 1, channel 2 and offset pulses, respectively. Asterisk legend: *** $p < 0.001$.

and intermittent stimulation by 21% is thought to be from the robustness of intermittent stimulation to the masking effect.

Subject 9 remarked that he was able to recognize two-channel intermittent stimuli as not only intensity patterns but also rhythmic patterns. This phenomenon was probably because of the fact that intensities of stimuli were modulated by the pulse width of each channel and the change of pulse width generated different rhythm in both channels. Some subjects might use the rhythmic patterns as subsidiary information together with intensity patterns to recognize two-channel stimuli, or to discriminate one-channel stimuli from two-channel stimuli which had definitely different rhythmic patterns to each other, leading to the increase of accuracy.

There was a big difference between two stimulation methods by 36% for the pattern 'weak/weak'. For simultaneous stimulation, 32% of 'weak/weak' was misidentified as 'weak/zero stimulus'. This is because the subjects were not able to discriminate 'weak' from 'zero' correctly due to adaptation of their perception to weak stimulus. On the other hand, robustness to the adaptation, which is a inherent characteristic of intermittent stimulation, made the subjects recognize weak stimulus with high accuracy even in long time trials over 30 minutes. This would be a favorable advantage in application to sensory feedback for a prosthesis where stimulation is given frequently and lasts long. Two robust characteristics of intermittent stimulation to masking and adaptation showed us the possibility of independent two-channel sensory feedback with high performance, where users would be able to recognize two different forces of the index and middle fingers independently even for long time use of a prosthesis.

It is expected that the accuracy for independent perception of two-channel stimulation would be raised as interchannel interval increases because stimulation times of the two channels become seperated further. At the same time, aliasing of feedback information might happen due to lengthened burst period which makes update speed of information slow in a channel. The performance for independent perception of two-channel information and the lossless transmission of information in a channel are in a trade-off relationship. Thorough experimental analysis for optimizing these two important factors should be conducted in the future.

B. Offset Pulses as a Virtual Channel

In the experiment 2, the marginal accuracies for channel 1 and 2 showed almost 100% with no statistically significant difference between them. This means the addition of the offset pulses as a virtual channel did not decrease the accuracies of existing channel. Even though the marginal accuracy for offset pulses had a significant difference with that for channel 1, it showed high performance over 90%. It implies that the stimuli of each channel were recognized somewhat independently, not confused with each other.

One three-channel electrotactile feedback [4] for encoding the thumb, index and middle fingers respectively also conducted the experiment in which the subjects identified location (on/off) of stimulation among three channels. In this experiment, the accuracy for recognizing the on/off state of each channel decreased by about 20% when two out of three channels were stimulated simultaneously compared to one-channel stimuli. From this, it was thought that added third channel seemed to hinder the recognition of the stimuli in existing channels. Actually there was no intensity difference between channels in the three-channel case. Thus, the addition of third channel only provided the binary information which had no magnitude. Therefore, it is better to use offset pulses in the existing channels as a virtual channel for the binary value rather than to add another electrode which makes confusion with the existing channel.

Offset plays important roles in determining relative intensity of tapping to pressure. Large offset would make pressure be masked by strong tapping and small offset fails to discriminate tapping from underlying pressure. It is important to find proper offset value for each subject considering their cognitive characteristic such as ST or PT. Further study should be conducted to investigate the values for the amplitude of 100Hz pulses and the offset of offset pulses to make them recognized independently as possible.

C. Justification of the Assumption

Equation (1) where thumb's force is approximately equal to the sum of forces of the index and middle fingers do not hold for every grasping case. In lateral pinch, which is a typical counterexample, the forces of the thumb, index and middle fingers are determined somewhat independently and the force of thumb cannot be predicted from that of the others. But just letting users know of the fact that thumb has contact with an object using offset pulses seems to be enough for stable grasping of a prosthetic hand because lateral pinch is usually used for holding thin and light objects like key or papers. Also, according to the statistical researches about grasping patterns used in daily living [11], [12], a percentage of the frequency and daily time where lateral pinch is used in a day was less than 10% which is quite low. Therefore, it is an advantage to replace thumb's force with the offset pulses for the cases of 90% where the assumption is reasonable rather than to assign one channel for thumb in terms of the efficiency of encoding of sensory information.

V. CONCLUSIONS

This work investigated two-channel electrotactile stimulation for sensory feedback of fingers of prosthesis. By replacing thumb's channel, which had redundant information, with offset pulses, grasping forces of three fingers were able to be encoded into the two channels. Through the experiments, we found that two-channel intermittent stimulation had better performance in recognition of intensity patterns than simultaneous stimulation. It implied the possibility for independent feedback of the forces of the index and middle fingers, which had not been tried before using three channels. Also, the offset pulses as a virtual channel were able to deliver the contact state of thumb without decreasing cognitive accuracy of two channels for the index and middle fingers. Therefore, two-channel sensory feedback could be a better solution than three-channel where the cognitive interference between channels was significant. To validate performance of the proposed method in grasping control of a prosthesis, future work is to be planned.

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