ELECTRO-CUTANEOUS PHANTOM SENSATION AS A SENSORY FEEDBACK METHOD

N.Hoshimiya, T.Izumi, M.Tsuruma, R.Futami, T.Ifukube and Y.Handa+

Res. Inst. of Applied Electricity, Hokkaido Univ., Sapporo, JAPAN
+ Dept. of Anat., Shinshu Univ. School of Med., Matsumoto, JAPAN

Abstract

A new presentation method as a sensory feedback for the control of the paralyzed upper extremities is proposed. Design parameters of the electro-cutaneous stimulation to the shoulder skin surface have been investigated.

Psychophysical properties of the normal subjects and a paralyzed patient to electrical stimulation have been examined. A fused image could be felt between two electrode pairs by presentation of the phantom sensation (PS). A moving image could be elicited when the stimulation amplitudes of two channels varied temporally and complementally. Quantitative characteristics on the perception of the PS image are shown.

Widely moving phantom image could be produced by three channel arrangement. The communication capacity of this method is also described.

Keywords

Sensory feedback, Electro-cutaneous stimulation, Phantom sensation, Functional electrical stimulation (FES), Quadriplegic patient

1. Introduction

Functional Electrical Stimulation (FES) or Functional Neuromuscular Stimulation (FNS) is very efficient for the restoration of the paralyzed upper extremities. Functional hand movements have been restored in C5-C6 quadriplegics by a microcomputer based multichannel FES system (1-7). Such patients are deprived of not only motor function but also sensory function. They have almost no sense at their hands even when some kinds of grasp are realized by the FES. To restore the sensation relating to the hand movements produced by the FES, a sensory feedback system should be equipped in a total system as shown in Fig.1. So, we have studied the electro-cutaneous stimulation to the patients' shoulder, since quadriplegic patients have enough tactile sense in the shoulders.

Important factors in the electro-cutaneous stimulation are as follows:

(1) Pulse intensity (pulse amplitude and/or pulse width)
(2) Pulse frequency
(3) Geometrical arrangement, i.e. spatial discrimination with multichannel system.

Several sorts of the features of electro-cutaneous sensory information presentation methods were reported by Solomonow et.al.(8-10), Riso et.al.(11,12) and Tachi et.al.(13). But there are still some fundamental difficulties, i.e. there are very big varieties among the characteristics of the electrode-skin-nerve system. Each system has different threshold current for electrical stimulation. Each system shows different sensation for the same stimulation intensity, i.e. it is not realistic to adjust all electrode-skin-nerve system in order to elicit the controllable sensation. In actual sensory feedback system, it is desirable to equip some facilities which make the patient feel moving sense reflecting finger movements etc.. But there has been no good method, because ordinary sensory feedback system required a lot of electrodes for this purpose. We introduced electrical phantom sensation (PS) to make them feel such sense(14). One can feel the moving sense between two pairs of stimulation electrodes. The amplitude of the current pulse trains applied to two separate electrode pairs are modulated complementally; one increases while the other decreases. The combination of two channel stimulation intensities must be determined in such a way that subjects can feel almost even sensation of a fused image.

2. Presentation of a moving phantom image.

Figure 2 shows the principle of the phantom sensation (PS) induced by a pair of electrical stimulation. We can feel a certain sensation as a fused image between two electrode pairs without any additional electrode pairs. The experimental setup is shown in Fig.3. Conventional commercially available Ag/AgCl electrodes for ECG recording with 10 mm diameter were placed on the shoulder skin of the normal subjects or a patient as shown in Fig.3. A pair of electrodes was used for bipolar stimulation. These were separated by 13 mm. Stimulation waveform is also shown in Fig.3. Monophasic constant current pulse train was adopted. Controllable parameters were as follows:

Pulse amplitude (PA)
Pulse width (PW)
Pulse frequency (PF)
Distance between two electrode pairs (L)

In the experiments, PW was fixed at 0.2 ms, so that PA was in the moderate range (1 to 10 mA). If we can feel the sense of stimulus in midway of two electrode pairs, the number of electrodes can be reduced. When stationary stimuli of two different amplitudes are applied to two pairs of electrodes placed separately with several centimeters interval, we feel fused image over the area, but it is difficult to recognize the stimulus in a localized area.

When two channel stimuli (I_0 and I_1), whose amplitude varied with time complementally to each other, were applied at the same moment to two pairs of electrodes, we could feel the sense of stimulus as a fused image moving between them. In Fig.4 envelopes of such stimulation patterns are shown. But the sense of stimulus at the middle of two pairs of electrodes was weaker than that under the electrodes in this case. On the other hand, we could feel the sense of moving stimulus quite homogeneously over the whole area between two electrode pairs, when specially designed stimuli were applied to the electrode pairs. Such set of stimulation patterns are schematically shown in Fig.5. Actually these stimulation waveforms were designed by the use of equal loudness contours shown in Fig.6. The contours were made in such a way that the amplitude of stimuli were balanced by the subject to feel the fused image with equal intensities by changing the combination of two amplitudes, even if the localization was not clear between the electrode pairs. Shapes of the curves were nearly elliptic. Smoothly moving clear phantom sensation (PS) images were elicited by the electrocutaneous stimulation with these envelopes. A PS image could be perceived as schematically shown in Fig.7.

The waveform generation method was based on the equal loudness contour, which was different from subject to subject. In order to evaluate the PS, or to generate waveforms in a consistent way for different subjects, we introduced a normalized presentation shown in Fig.8. I_0 and I_1 in both axes in Fig.8 are normalized here as $I_0/\bar{I}_0$ and $I_1/\bar{I}_1$, where $\bar{I}_0$ and $\bar{I}_1$ are average values of I_0 and I_1, respectively. We can feel moderate sense of stimulation with almost even magnitude for both cases, i.e. $I_0=\bar{I}_0, I_1=0$ and $I_0=0, I_1=\bar{I}_1$. In this diagram, the degree of the amplitude change is represented by theta, and the frequency of the amplitude change is indicated by VF. In fact the PS image could be felt to move between electrode pairs with the frequency VF.

3. Characteristics on the PS image perception

There was threshold in theta to feel the fused image, and it varied with pulse frequency (PF) as shown in Fig.9. For comfortable phantom sensation, PF=100 Hz was recommended.

Theta had weak dependence on the modulation frequency (VF) as shown in Fig.10. For clear phantom image presentation, VF=1 to 2 Hz was recommended.

Threshold value of theta also varied with pulse amplitude (PA) as shown in Fig.11. In Fig.11, pulse amplitude ($\bar{I}$) was normalized by the absolute threshold for stational stimulation. When pulse amplitude ($\bar{I}$) was small, it was difficult to feel PS. If $\bar{I}$ was too large, we tended to get pain by the stimuli. To perceive moderate and smoothly moving PS image, $\bar{I}$ applied to each channel must be in the range from 1.5 to 2.5 times over the absolute threshold value.

PS image perception depended upon electrode pair interval (L). As shown in Fig.12, there was a preferable range for L to elicit clear PS image. And the range had some relation to the spatial resolution characteristics of subjects. Two solid curves indicated the rate of perception of fused images to stational two channel electric stimuli and mechanical pressure stimuli using a pair of wooden compasses, respectively. Two kind of two point discrimination threshold (Eth,Mth) were defined by the value of L on which the rate was 0.5. One to the electric stimuli was indicated as Eth and the other to mechanical stimuli as Mth, respectively. Eth and Mth were not quite different from each other. It is time consuming to measure Eth with many electrodes. On the contrary, it is very easy to find Mth with simple wooden compasses. So we can estimate spatial resolution characteristics to electrical stimulation by mechanical parameter Mth.

When L was equal to Mth or a little larger, PS was perceived very well. Since spatial characteristics have big variety among subjects, the electrode pair interval (L) must be properly specified for each subject.

In Fig.5, two channel stimulation pattern (I_0 and I_1) produced a phantom image. In this case, the image moved from ch.0 to ch.1, and then moved back to ch.0. As a natural extension, three channel phantom image presentation could be considered. Three channel electrode pairs were placed on a line as shown in Fig.13. It was found that combination of three channel stimulation patterns I_0, I_1 and I_2 shown in Fig.14 could produce a widely moving phantom image. In this case, the image moved from ch.0 to ch.1, and then moved further to ch.2. After then it moved back from ch.2 to ch.1, then further moved back to ch.0.

We could feel smoothly moving continuous sensation over wide area on the shoulder. On further extension, we could feel it over the whole area from left shoulder to right shoulder by 4 or 5 channel stimulation.

It was confirmed that experimental evidence about the PS image perception described above were basically consistent even in case of a C4 quadriplegic patient.

4. Category identification by the PS

We examined the discrimination test on the PS both in two channel and in three channel system. In two channel system, four categories corresponding to four perceived areas of the moving image shown in Fig.15(a) were produced by combinations of stimulation currents illustrated in Fig.15(b). Similar categorization was also adopted in three channel system (Fig.16). Discrimination tests were performed in the following way: Four test patterns (i.e. four categories) were randomly presented 20 times so that overall 80 times stimulation were done in each subject. After every trial, correct answer was revealed to the subject on the CRT display of the microcomputer.

Experimental results are shown in Fig.17 and Fig.18. In the two channel PS category identification test, rate of correct recognition (RCR) was about 70 to 80 %, and it had no strong dependence on the modulation frequency (VF). In the three channel test, RCR was about 90 to 100 %, and it had also no strong dependence on VF. It should be noticed that RCR was almost 100 % for the condition of L=80 mm and theta=60 degrees. This means that the information was recognized with high reliability in this condition.

To discriminate categories correctly, amplitude variation factor theta must be larger than a certain value. In Fig.18 RCR was saturated where theta was larger than 20 degrees.

We also examined dependence of RCR and information transmission (ITR) upon category number (N). In this case, N test patterns were presented 10 times so that N*10 times stimulation were done. Experimental results are shown in Fig.19 and Fig.20 for two and three channel system, respectively. In both cases, RCR decreased with N so that ITR increased with N and then was saturated.

It is preferable for reliable communication to obtain high RCR. If we assume that RCR must be more than 80% for reliable communication, the largest N is 5 and then ITR is 1.6 [bits/symbol] in 2 channel presentation method. In 3 channel presentation, the largest N is also 5 and ITR is 1.7 [bits/symbol] for the same condition.

5. Conclusion

A new presentation method as a sensory feedback for the control of the paralyzed upper extremities was proposed. Psychophysical properties of normal subjects and a C4 quadriplegic patient to surface electrical stimulation were examined. It was disclosed that a moving fused phantom image could be clearly elicited between two electrode pairs. This was realized by stimulation waveforms which varied temporally and complementally each other. Furthermore, widely moving phantom image could be produced by three or more channel arrangement, which enabled us to offer more reliable discrimination for sensory feedback.

This new strategy will be combined with the conventional sensory feedback techniques (AM or FM stimulation) to offer essential information, e.g. finger displacement, velocity and grasping pressure, to quadriplegic patients.

Acknowledgement

This work was supported by the Ministry of Education, Science and Culture of Japan under a Grant-in-Aid for Developmental Scientific Research No.60850073(1985-1986).

References

1) P.H.Peckham, J.T.Mortimer, E.B.Marsolais: Controlled Prehension and Release in the C5 Quadriplegic Elicited by Functional Electrical Stimulation of the Paralyzed Forearm Musculature, Ann. Biomed. Eng., 8, pp.369-388(1980).
2) Y.Handa, Y.Shimada, S.Komatsu, A.Naito, M.Ichie, Y.Nakatsuchi, R.Yagi, Y.Sugimoto, K.Iijima, R.Futami and N.Hoshimiya: Electrically Induced Hand Movements and Their Application for Daily Living, Proc. 8th International Symposium on External Control of Human Extremities, pp.169-180(Dubrovnik,1984).
3) Y.Handa, M.Ichie, T.Handa, R.Yagi and N.Hoshimiya: Control of the Paralyzed Hand by a Computer-controlled FES System, IEEE/7th Ann. Conf. Eng. in Med. & Biol., pp.322-326(Chicago,1985).
4) N.Hoshimiya, K.Iijima, R.Futami, Y.Handa and M.Ichie: A New FES System for the Paralyzed Upper Extremities, IEEE/7th Ann. Conf. Eng. in Med. & Biol., pp.327-330(Chicago,1985).
5) M.Ichie, Y.Handa, A.Naito, T.Handa, N.Matsushita and N.Hoshimiya: EMG Analysis of the Thumb and its Application to FNS, IEEE/8th Ann. Conf. Eng. in Med. & Biol., pp.538-540(Fortworth,1986).
6) N.Matsushita, Y.Handa, M.Ichie, A.Naito, T.Handa and N.Hoshimiya: Analysis of Wrist Movements and its Application to FNS, IEEE/8th Ann. Conf. Eng. in Med. & Biol., pp.618-619(Fortworth,1986).
7) Y.Handa, T.Handa and N.Hoshimiya: A Portable FNS System for the Paralyzed Upper Extremities, IEEE/8th Ann. Conf. Eng. in Med. & Biol., pp.658-660(Fortworth,1986).
8) M.Solomonow, J.Lyman and A.Freedy: Electrotactile Two-Point Discrimination as a Function of Frequency, Body Site, Laterality, and Stimulation Codes, Annals of Biomedical Engineering, 5, pp.47-60(1977).
9) M.Solomonow and J.Lyman: Artificial Sensory Communications via the Tactile Sense; Space and Frequency Optimal Displays, Annals of Biomedical Engineering, 5, pp.273-286(1977).
10) M.Solomonow, L.Raplee and J.Lyman: Electrotactile Two Point Discrimination as a Function of Frequency, Pulse Width and Pulse

Time Delay, Annals of Biomedical Engineering, 6, pp.117-125(1978).
11) R.R.Riso, A.Y.J.Szeto and M.W.Keith: Comparison of Subdermal versus Surface Electrocutaneous Stimulation, IEEE Front. Eng. in Health Care, pp.343-347(1982).
12) R.R.Riso, M.W.Keith, K.R.Gates and A.R.Ignagni: Subdermal Stimulation for Electrocutaneous Communication, 6th Ann. Conf. Reh. Eng., pp.321-323(San Diego, 1983).
13) S.Tachi, K.Tanie, K.Komoriya and M.Abe: Electrocutaneous Communication in a Guide Dog Robot(MELDOG), IEEE Trans. Biomed. Eng., BME-32, pp.461-469(1985).
14) N.Hoshimiya, T.Izumi, A.Fujii, R.Futami, T.Ifukube and Y.Handa: Sensory Feedback for the "FNS" System, IEEE/8th Ann. Conf. Eng. in Med. & Biol., pp.661-663(Fortworth,1986).

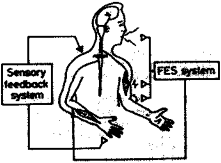


Fig.1 Total FES system for the restoration of paralyzed upper extremities with sensory feedback system.

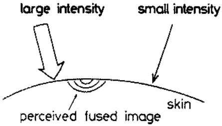


Fig.2 Principle of the phantom sensation (PS).

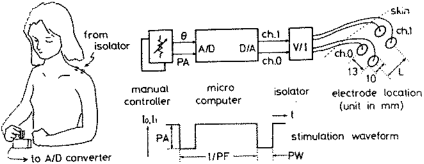


Fig.3 Experimental setup and stimulation parameters.
PA: pulse amplitude PF: pulse frequency
PW: pulse width L: distance between electrode pairs

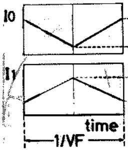


Fig.4 A set of envelopes of stimulation currents varying linearly and complementally.

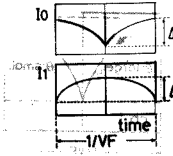


Fig.5 A reformed pattern of stimulation current envelopes.

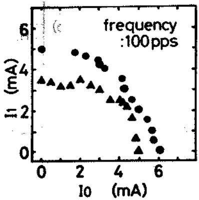


Fig.6 Equal loudness contours.
(magnitude of sensation
●:large,▲:small)

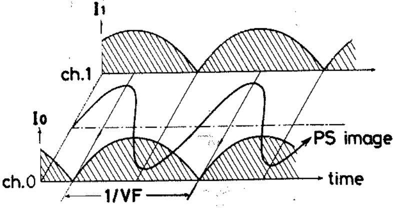


Fig.7 Schematic representation of PS image perception.

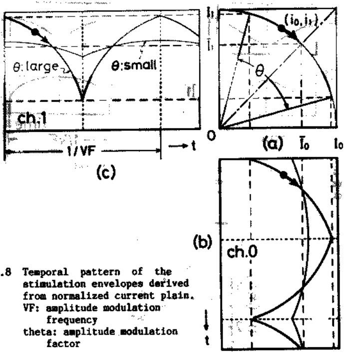


Fig.8 Temporal pattern of the stimulation envelopes derived from normalized current plain.
VF: amplitude modulation frequency
theta: amplitude modulation factor

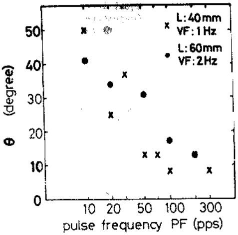
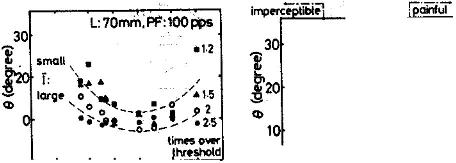


Fig.9 Dependence of PS image perception on pulse frequency PF.



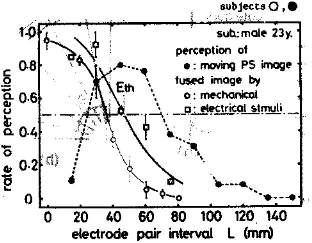


Fig.12 Dependence of both PS image perception and spatial resolution on distance between electrode pairs L.

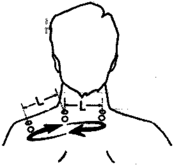


Fig.13 PS image elicited with three electrode pairs.

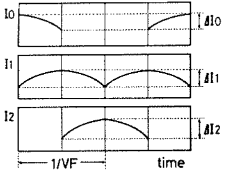


Fig.14 A set of envelopes of stimulation currents applied to three channels.

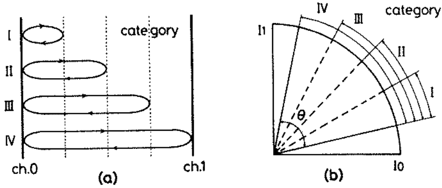


Fig.15 Category presentation. (a) Schematic presentation of four perceived images elicited with two channel stimulation. (b) Four orbits in the stimulation currents plain with category number.

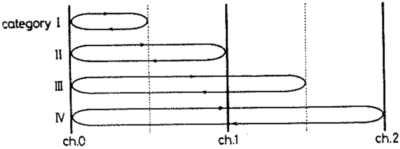


Fig.16 Schematic presentation of four perceived images elicited with three channel stimulation.

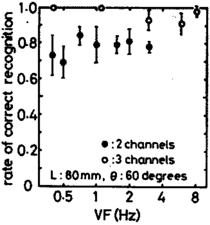


Fig.17 Relation between RCR and VF in four category test.

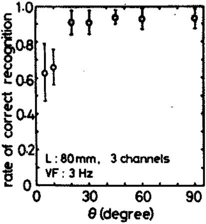


Fig.18 Relation between RCR and theta in four category test.

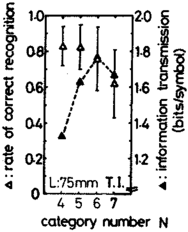


Fig.19 RCR and ITR versus category number N with two channel system.

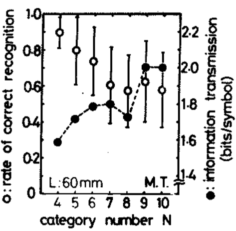


Fig.20 RCR and ITR versus category number N with three channel