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Low-frequency electrical therapy with chaotic vibration and its performance analysis

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Abstract—In this paper, we analyzed what kind of psychological effects chaotic vibrations have and how long these effects last. To resolve this issue, we produced chaotic low-frequency electrical therapy device to generate chaotic vibrations. Using the chaotic low-frequency electrical therapy device, we analyzed direct effects of the chaotic vibration on the human body. In the experiments, we generated periodic vibration, fully chaotic vibration and intermittent chaotic vibration. To evaluate the effects of the vibration on the human body, we used one of the subjective methods, a paired-comparison method. We identified a rank-order scale by comparing pairs of the two vibrations. The results indicate that the chaotic vibration is more effective than the periodic vibration.

1. Introduction

In our daily life, we often observe various kinds of complex phenomena, for example, temperature variations, seismic activities of earthquakes, biological signals such as brain waves, breathing rate and cardiac rhythms. These complex phenomena could be generated from deterministic nonlinear dynamical systems or stochastic systems. Researches on nonlinear vibrations usually try to reveal underlying mechanisms of such complicated vibrations by applying model analysis, bifurcation analysis, and time-series analysis toward high-performance prediction and control. In our research, we investigate how such complicated vibrations affect to human bodies directly. In particular, we focused on the chaotic vibrations generated from chaotic dynamical systems. We also introduce chaotic vibrations with $1/f$ structure that have already been acknowledged to have positive effects on human bodies indirectly.

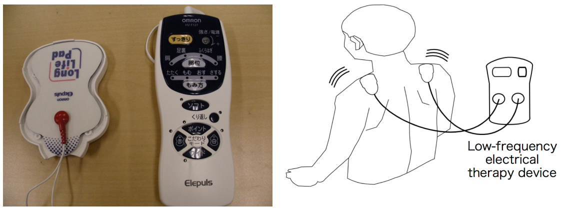
Low-frequency electrical therapy devices and EMS (Electronic neuro-Muscular Stimulation) devices are typical examples of applications of electrostimulations for medical treatments such as mitigation of throbbing pains and therapy of muscles. It has been reported that muscle contraction by electrostimulation encourages rehabilitation of paraplegics moves[1, 2]. These results of positive effects by electrostimulation indicate that it is important to develop an effective electrostimulation method.

In this paper, we investigated how electrical complicated vibrations, such as chaotic dynamics, affect human bodies. Then we produced a new device with chaotic electrical vibrations and analyzed its effects by experiments. To realize this issue, firstly, we analyzed output characteristics of a low-frequency electrical therapy device which is commercially available. Then, we confirmed that its outputs are not complex but periodic. Next, we investigated electrical components of the low-frequency electrical therapy device. By modifying this commercial device, we made a new device that generates chaotic electrical vibrations and estimated its effects on human bodies. To estimate the effectiveness, we used subjective evaluation as an estimation method. Although several subjective evaluation models have already been proposed, we used Thurstone's paired-comparison method[3]. In the experiments, we adopted three kinds of stimuli, namely, chaotic, intermittent chaotic and periodic vibrations. The experiments and statistical analysis show that effectiveness of the chaotic vibration and the intermittent chaotic vibration is almost the same, and the periodic vibration is the least effective.

2. How to make the chaotic vibration generator

The low-frequency electrical therapy device "Elepuls HV-F127" manufactured by Omron Corp. is a device used for electrical therapy. It uses pads attached to the surface of the human body. Elepuls causes contraction and flaccid of muscles by stimulating with electronic pulses. Example of an output waveform is shown in Fig.2. By the electrostimulation, it reduces the stiffness out of a neck, relieves pains of muscles or recovers from its fatigues.

The Elepuls realizes various types of electrostimulation called "modes" by repeatedly generating rectangular



(a) (b)

Figure 1: (a) Overview of “Elepuls HV-F127” manufactured by Omron Corp. (b) Schematic diagram of how to use the Elepuls.

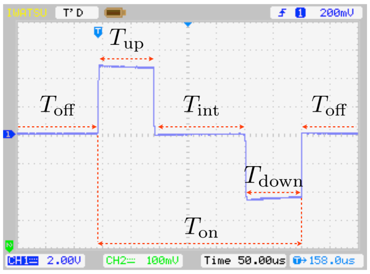


Figure 2: An output waveform of the Elepuls.

pulses (Fig.2) and combining these pulses in several ways. Among several modes, we used the patting mode. In the patting mode, T_{off} varies while $T_{\text{on}}(= T_{\text{up}} + T_{\text{down}} + T_{\text{int}})$ is constant. When the pulse arises (T_{on}), one can feel electrostimulation. Then, T_{off} corresponds to an interval of a single patting. Namely, T_{off} is a control parameter of patting frequency. In this paper, by modulating T_{off} by a chaotic map, we realized a chaotic patting mode in which intervals of the patting are chaotic.

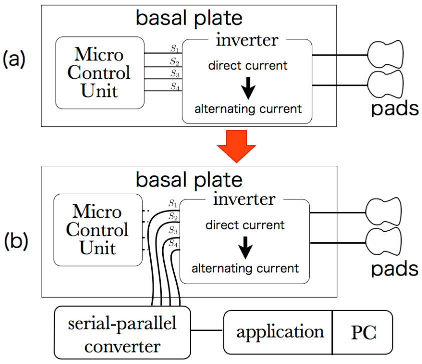


Figure 3: (a) Schematic view of the inner structure of the Elepuls and (b) the remodelled Elepuls.

Figure 3(a) is a schematic view of the inner structure of the Elepuls. On the basal plate of the Elepuls, micro control units (MCU) controls timings of flipping switches by sending signals to four switching elements of the inverter. Then, the pulses are transmitted to the human body through the pads. In the MCU, switching timings are programmed as the modes. Thus, to change a periodic output to a chaotic output, we controlled the switching timings of the inverter.

Firstly, as shown in Fig.3(b), using a personal computer (PC) as a controller, we implemented a device which converts serial signals sent by the PC to 4-bit parallel signals using a serial-parallel converter, USB-8-bit parallel converter IC manufactured by FTDI Corp.[6]. Next, to control the switching timings by the parallel signals, we cut off wires connecting MCU to four switching elements of the inverter and connected each signal wire of the converter to the switching elements. Figure 4 shows the overview of the chaotic vibration generator. Next, we controlled the switching timings by using two maps. The first map is the logistic map[4]:

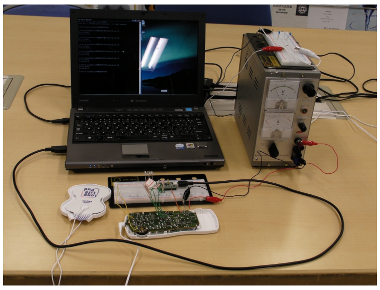


Figure 4: The overview of the chaotic vibration generator.

$$x(t+1) = ax(t)(1 - x(t)). \tag{1}$$

In Eq.(1), we set $a = 4$ to produce a fully chaotic time series. The second map is a modified Bernoulli map[5]:

$$x(t+1) = \begin{cases} x(t) + 2^{B-1}(1-2\epsilon)x(t)^B + \epsilon \\ \qquad (0 \leq x(t) < 1/2)\,, \\ x(t) - 2^{B-1}(1-2\epsilon)(1-x(t))^B - \epsilon \\ \qquad (1/2 \leq x(t) \leq 1)\,, \end{cases} \tag{2}$$

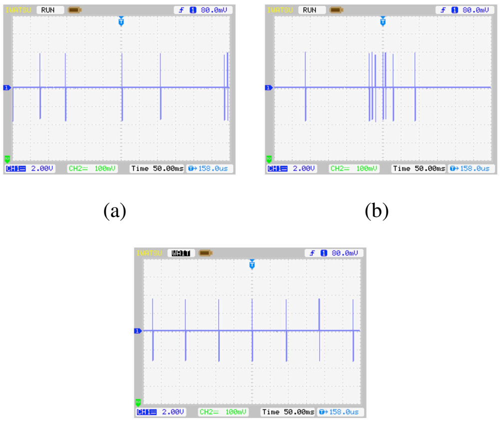
where we set $B = 2.0$ and $\epsilon = 1.0 \times 10^{-5}$ to produce intermittent chaotic response which shows a $1/f$ spectral structure. In the modified patting mode of the chaotic vibration generator, we transformed the outputs from these chaotic maps to T_{off} by the following equation:

$$T_{\text{off}}(t) = \frac{\max(\mathrm{T}_{\text{off}}) - \min(\mathrm{T}_{\text{off}})}{\max(x) - \min(x)} \times x(t) + \min(\mathrm{T}_{\text{off}}) \tag{3}$$

where T_{off} indicates a temporal interval of electrostimulation, $\max(T_{\text{off}})$ and $\min(T_{\text{off}})$ indicate the maximum value and the minimum value of T_{off}, and $\max(x)$ and $\min(x)$ are the maximum and the minimum values of $x(t)$ obtained by Eqs.(1) or (2).

Figure 5 shows output waveforms. In Fig.5, one vertical bar represents one set of rectangular pulses shown in

Fig.2 (the scale is minified). Then, intervals between the vertical bars correspond to T_{off}. Figure 5 (a) and (b) show chaotic waveforms, while Fig.5(c) shows a periodic waveform. These results show that we could control the timings to output rectangular pulses arbitrarily by our chaotic vibration generator.



(a) (b)

(c)

Figure 5: Examples of generated outputs by the chaotic vibration generator when max(T_{off}) = 165.0 [ms], min(T_{off}) = 2.0 [ms]. (a), (b) chaotic waveforms with the parameter $a = 4.0$ and (c) a periodic waveform with $a = 2.0$.

3. The paired comparison method

Thurstone's paired-comparison method[3] identifies a rank-order scale of several complicated stimuli. For example, it is not so easy to identify an order of preferred foods when several foods are just given. However, if we are asked to compare two foods, we can easily choose a favorite food. Namely, the pair-comparison offers an easy way to judge among several targets. Then, in this paper, we used Thurstone's paired-comparison method as subjective evaluation. To calculate a rank-order scale from data obtained by the pair-comparison, a measurement model which represents a process of distinguishing stimuli is used. Even if we are stimulated by the same stimuli, we often show different psychological responses. Namely, the psychological responses obey a distribution.

First, we defined a set of k stimuli $A = \{a_1, a_2, \ldots, a_k\}$ as a subject of psychological measurements. Next, we defined u_i as a random variable corresponding to psychological measurements when the stimulus a_i is given and u_i obeys normal distribution $N(\alpha_i, \sigma_i^2)$. Then, the probability that $a_i \succ a_j$ (a stimulus a_i is superior to a_j) is equal to the probability that a random value $u_i \geq u_j$, as shown in the following equation:

$$P(a_i \succ a_j) = P(u_i - u_j > 0). \tag{4}$$

In Eq.(4), the distribution of $u_i - u_j$ obeys $N(\alpha_i - \alpha_j, \sigma_{i-j}^2)$, and α_i is a rank-order value of the psychological response when a stimulus a_i is given. If the psychological responses are independent, the variance σ_{i-j}^2 becomes $\sigma_i^2 + \sigma_j^2$.

Let us define $d_{ij} = u_i - u_j$ and normalize d_{ij} by σ_{i-j};

$$z = (d_{ij} - (\alpha_i - \alpha_j))/\sigma_{i-j}. \tag{5}$$

In addition, $\pi_{ij} = P(u_i - u_j > 0)$ can be described by using the standard normal distribution function Φ as follows,

$$\begin{aligned} \pi_{ij} &= P(d_{ij} > 0) \\ &= P(z < (\alpha_i - \alpha_j)/\sigma_{i-j}) \\ &= \Phi((\alpha_i - \alpha_j)/\sigma_{i-j}). \end{aligned} \tag{6}$$

By using Φ^{-1}, we can transform Eq.(6) to Eq.(7):

$$\Phi^{-1}(\pi_{ij}) = \frac{\alpha_i - \alpha_j}{\sigma_{i-j}}, \tag{7}$$

where π_{ij} is the true value of the probability(Eq.(4)). However, we cannot know the true value of π_{ij} generally. Instead, we use p_{ij} as estimated π_{ij}, which represents the number of subjects who judged that a stimulus a_i was superior to a stimulus a_j. Then in Eq.(4), we assume that all σ_{i-j}'s are constant and equal to unity to uniquely determine the solution of Eq.(7). Thus, the model is described by

$$\Phi^{-1}(\pi_{ij}) = \alpha_i - \alpha_j. \tag{8}$$

Table 1 shows a relation between the model and data. The average of each row is $\alpha_i - \bar{\alpha}$. We can consider $\bar{\alpha} = 0$, without the loss of generality. Then, the average of each row corresponds to presumed values α_i of a rank-order.

Table 1: Relation between the model and data. α_i is a rank-order value of the psychological response when a stimulus a_i is given, and Φ is the standard normal distribution function.

a_j a_i	a_1	a_2	a_3
a_1	$\Phi^{-1}(p_{11}) =$ $\alpha_1 - \alpha_1$	$\Phi^{-1}(p_{12}) =$ $\alpha_1 - \alpha_2$	$\Phi^{-1}(p_{13}) =$ $\alpha_1 - \alpha_3$
a_2	$\Phi^{-1}(p_{21}) =$ $\alpha_2 - \alpha_1$	$\Phi^{-1}(p_{22}) =$ $\alpha_2 - \alpha_2$	$\Phi^{-1}(p_{23}) =$ $\alpha_2 - \alpha_3$
a_3	$\Phi^{-1}(p_{31}) =$ $\alpha_3 - \alpha_1$	$\Phi^{-1}(p_{32}) =$ $\alpha_3 - \alpha_2$	$\Phi^{-1}(p_{33}) =$ $\alpha_3 - \alpha_3$

4. Experimental conditions

We conducted experiments on 12 subjects who have stiffness. The process of the experiments is understood by these subjects. In this experiment, the subjects spent a time as usual. When they finished their daily works, we gave a stimulus for 10 minutes at the condition that subjects sat down on a chair. We attached the pads to a part where subjects claimed a stiffness. We used three kinds of stimuli described below.

1. The chaotic vibration produced by the logistic map[4] (Eq.(1)) with $\max(\mathrm{T_{off}}) = 1,000$ [ms] and $\min(\mathrm{T_{off}}) = 400$ [ms].
2. The intermittent chaotic vibration produced by the modified Bernoulli map[5] (Eq.(2)) with $\max(\mathrm{T_{off}}) = 1,000$ [ms] and $\min(\mathrm{T_{off}}) = 400$ [ms].
3. The periodic vibration with $T_{\mathrm{off}} = 720$ [ms].

We compared all possible pairs of two stimuli among these three stimuli. We randomly choose a pair from these three pairs (A, B and C). Then we conducted the pair-comparison. When we used the pair A, first we gave a stimulus randomly among the pairs to the subject. The next day, we gave another stimulus. Then we have a subject answer of which stimulus was better from a viewpoint of the feeling and body conditions after the experiment on the third day. We also repeated the same procedure to the pairs B and C, and the experiment is conducted during 3 days × 3 pairs = 9 days.

5. Results and discussions

Table 2: Results of the paired-comparison. Each element indicates the number of subjects who have judged that the stimulus corresponding to the row was better than that corresponding to the column. Therefore, diagonal elements are not taken into account and represented by "–". For example, the number "2" of the (3, 1)th entry in the table indicates that the number of subjects is two, who have judged that the periodic vibrations was better than the chaotic vibrations.

	chaotic	intermittent chaotic	periodic
chaotic	–	6	10
intermittent chaotic	6	–	10
periodic	2	2	–

Table 2 shows data obtained by the paired-comparison. We obtained the rank-order scale shown in Fig.6 from the results of Table 2. The results indicate that the effectiveness of the chaotic vibration and the intermittent chaotic vibration is the same, and is better than the periodic vibration.

Next, we tested validity of the rank-order value (Fig.6) by χ^2 test, because the model has some assumptions. As a result, $\chi^2 = 0.14$ is smaller than the value of χ^2 with the 1 degree of freedom is 1 and confidence interval of 95% ($\chi^2 = 3.84$). This result indicates that the rank-order values obtained by applying the model (Eq.(8)) to the paired-comparison data (Table 2) are reliable, however we could not show the difference of the chaotic vibration and the intermittent chaotic vibration. In this sense, one of the important future work is to increase the number of subjects to show how the difference between the stimuli is significant. It is also an important issue to show the reproducibility of the paired-comparison data.

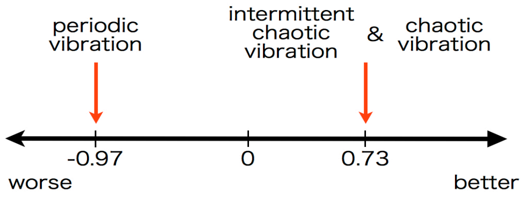


Figure 6: Results of the rank-order scale of three stimuli by the paired-comparison method.

6. Conclusion

We produced a chaotic vibration generator by modifying the low-frequency electrical therapy device which is commercially available. We analyzed how does it affect to human bodies. The data we obtained by the experiment indicate that the complex vibrations are better than the periodic vibration.

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