Localization Ability and Polarity Effect of Underwater Electro-Tactile Stimulation

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Abstract. In this paper, we describe a method for presenting underwater tactile electrical stimulation for in-bath entertainment. We investigated the localization abilities of participants and the polarity effect of the stimulation, and found that underwater electro-tactile anodic stimulation produced a stronger sensation than did cathodic stimulation. Furthermore, we found that the participants were able to successfully identify the direction of the tactile stimulation and the direction of rotation during anodic stimulation.

Keywords: Electrical stimulation, Haptic device, Human interface, Underwater stimulation

1 Introduction

Many people around the world take a daily bath. It is a relaxing moment, in which some of us sing, others read books, and waterproof tablets have enabled others to watch movies in the bath. There have been several attempts to develop novel, bath-specific entertainment, such as systems for playing music [1] and video games [2].

All of these existing bath time activities center on audio-visual information. However, we believe that there is room to enrich the bath experience by adding entertainment that focuses on the tactile modality. While numerous researchers have attempted to enrich entertainment systems by introducing whole-body tactile displays [3, 4], few of these have addressed underwater situations, with the exception of the ultrasonic tactile display described by Iwamoto et al. [5]. In their study, they used an ultrasonic transducer and a sonic lens, both located underwater, and generated pressure at the focal point of the lens. However, their setup required participants to cover their skin to prevent bodily penetration of the ultrasound signal. Thus, this approach is not applicable to a bath situation. Jetted tubs can be used for tactile presentation but are noisy and have poor temporal resolution.

This paper describes a method of presenting underwater tactile electrical stimulation. Electro-tactile displays are small and thin, affordable, energy efficient, and dura-

adfa, p. 1, 2011.

ble, making them useful for work in various fields [6, 7, 8]. Underwater electrical stimulation was developed mainly for massage [9], and it is well known that tactile sensations can be elicited in an electric-bath. To the best of our knowledge, no researchers have attempted to use underwater electro-tactile stimulation for entertainment. Thus, the potential of a whole-body tactile interface has not been fully explored.

As a first step in investigating the possibilities of underwater electro-tactile stimulation for in-bath entertainment, we investigated the ability of participants to localize the stimulation and identify the polarity effect of the stimulation. For safety, the electro-tactile stimulation was conducted using the forearm so that the current could not pass through the heart.

2 System Overview

We fabricated an underwater electrical stimulation device (**Fig. 1**). The device comprised a water tank, current controlled electrical stimulator circuit and eight electrodes. The electrodes were independently current-controlled. We used stainless steel plates that were 150 mm in height by 30 mm in width as electrodes, and placed these at regular intervals inside the tank. The diameter of the circle of electrodes was 100 mm.

Fig. 2 shows the system configuration. A voltage pulse wave is generated by a microcontroller (mbed, NCP LPC 1768, NXP Semiconductors) and offset circuit. The voltage waveform is converted to a current waveform of ±50mA by a voltage-current converter using high-voltage op-amps (OPA552, Texas Instruments), and emitted to the water by the electrodes.

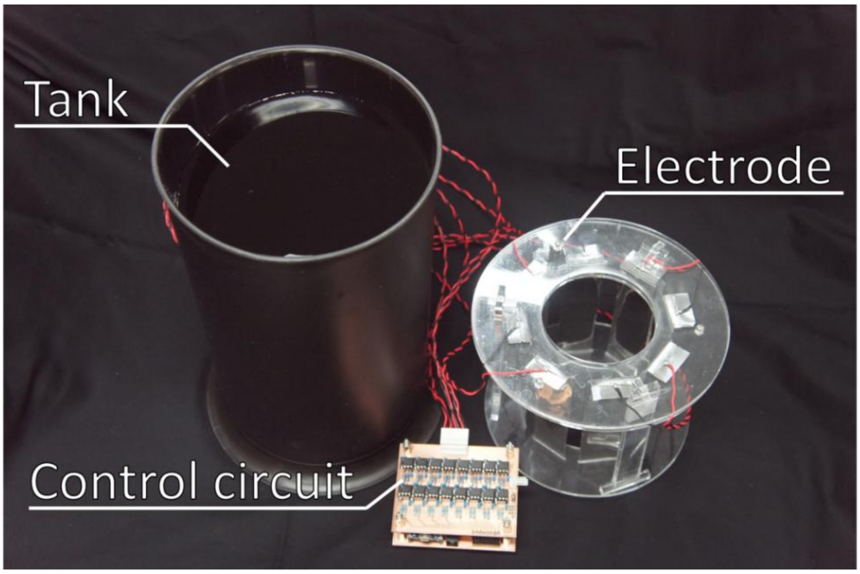

Fig. 1. Prototype system

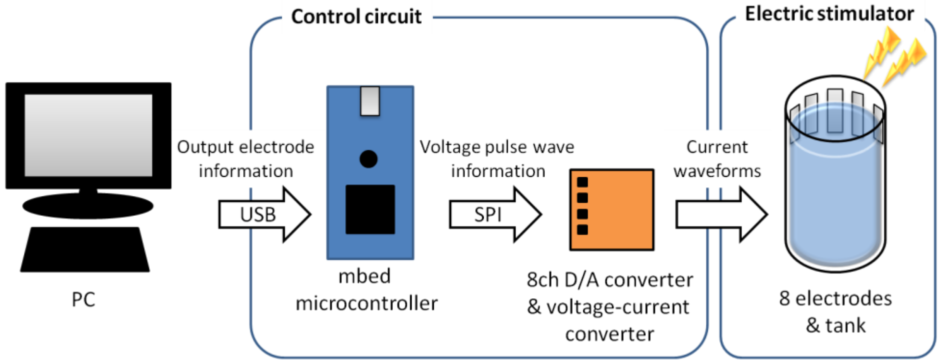

Fig. 2. System configuration

The safety of the system was assured as follows. The device was current controlled, meaning that the amount of stimulation did not increase even if the user touched the electrode. According to a guidance document for powered muscle stimulator (510(k)s U.S. FDA), the maximum power density should be less than 0.25 Watts/cm^2 [10]. In our device, the maximum current was 50 mA, the maximum voltage was 30 V, the maximum pulse width was 2 ms, and the maximum frequency was 28.5 Hz. Therefore, the maximum power of one electrode was:

$$50 \text{ mA} \times 30 \text{ V} \times 2 \text{ ms} \times 28.5 \text{ Hz} = 0.0855 \text{ W}.$$

As the size of the electrodes was 45cm^2, the amount of heat generated per unit area was:

$$0.0855 / 45 = 0.0019 \text{ W/cm}^2.$$

Consequently, our device was well below the limitations for electrical stimulation devices.

3 Experiment

We conducted an experiment to investigate the ability of participants to localize the stimulation and to identify the polarity effect of the underwater electro-tactile stimulation.

3.1 Experimental Condition

We used a burst pulse wave (**Fig. 3**). The pulse width was 2 ms, the pulse cycle was 35 ms, the burst width was 700 ms, and the rest time was 1000 ms. The rest time was set to prevent adaptation. The pulse amplitude was fixed to 50 mA.

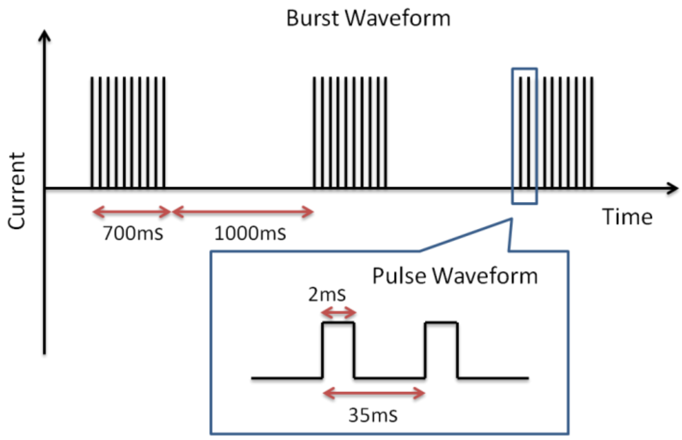

Fig. 3. Output waveform (anodic stimulation condition)

We used one electrode as a stimulating electrode and the other seven electrodes as returning electrodes. To observe the polarity effect of the electrical stimulation, we set the stimulating electrode output pulse to 50 mA (anodic stimulation) or -50 mA (cathodic stimulation). The output of the returning electrodes was set at -7.14 mA or 7.14 mA so that total current was balanced to 0 (50/7=7.14) (**Fig. 4**).

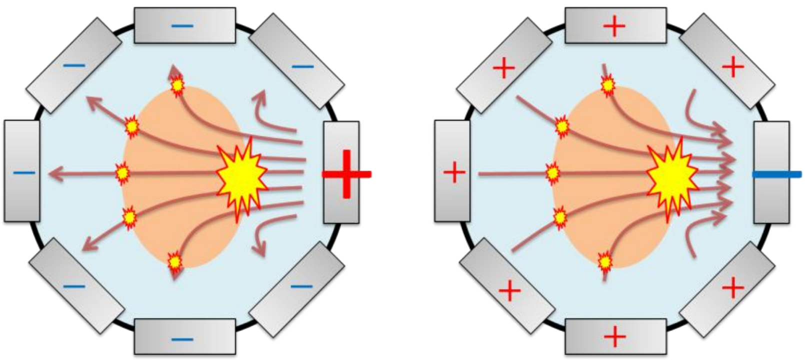

Fig. 4. Left: Anodic stimulation, Right: Cathodic stimulation

3.2 Procedure

We recruited six laboratory members aged 21-29 (all male) as participants. The experiment was conducted in two parts. In the first part, the eight electrodes were named from A to H. The participants put their left forearm in the tank and held a handle that was attached to the bottom of the tank so that the ventral forearm faced electrode C, and the back of the forearm faced electrode G (**Fig. 5**). The participants were asked to identify the direction of the stimulation from nine choices (A-H or “do not feel anything”). Each electrode was selected five times for each polarity, resulting in 5×2×8=80 randomized trials.

In the second part of the experiment, we presented a rotating stimulation by switching the stimulation electrode sequentially from one burst to the next (the burst width was 177 ms, and the rest time was 353 ms). The participants were asked to identify the direction of rotation from three choices (Right, Left, or “do not feel anything”). Each direction was selected five times for each polarity, resulting in 5×2×2=20 randomized trials.

Fig. 5. Overview of experiment

3.3 Results

Table 1 and **Table 2** show confusion matrices containing the participant answers and the actual locations of the anodic and cathodic stimulation. **Table 3** shows a confusion matrix containing the participant answers and the actual directions of rotation.

One clear observation is that anodic stimulation produced a much higher frequency of correct answers than did cathodic stimulation. As the answer “nothing is felt” was the most common answer in the cathodic stimulation trials, we suggest that two polarities have different thresholds. Note that we fixed the amplitude of the stimulating current to 50 mA, and we did not adjust between the polarities or among participants. In the anodic stimulation trials, participants identified the correct direction 47.9% of the time, on average. When we added the neighboring directions into the analysis (i.e. H and B for electrode A), participants identified the correct direction 81.3% of the time, on average. The participants made the following comments: “I felt vibration”, “I felt I was being tapped”, “I felt a soft touch”, “I felt my muscle move” and “I felt part of my hand move”. They were able to identify the direction of rotation 68.3% of the time.

Table 1. Confusion matrix containing correct participant answers and the actual location of stimulation (anodic stimulation)

Displayed \ Answered	A	B	C	D	E	F	G	H	nothing
A	40.0%	10.0%	0.0%	3.3%	6.7%	0.0%	0.0%	20.0%	20.0%
B	6.7%	70.0%	16.7%	0.0%	0.0%	0.0%	0.0%	0.0%	6.7%
C	6.7%	26.7%	26.7%	16.7%	0.0%	3.3%	10.0%	0.0%	10.0%
D	0.0%	3.3%	6.7%	40.0%	23.3%	0.0%	0.0%	0.0%	26.7%
E	3.3%	0.0%	3.3%	13.3%	53.3%	13.3%	6.7%	0.0%	6.7%
F	0.0%	0.0%	0.0%	0.0%	33.3%	60.0%	3.3%	0.0%	3.3%
G	0.0%	16.7%	0.0%	0.0%	3.3%	20.0%	50.0%	10.0%	0.0%
H	23.3%	3.3%	0.0%	3.3%	0.0%	0.0%	23.3%	43.3%	3.3%

Table 2. Confusion matrix containing correct participant answers and actual location of stimulation (cathodic stimulation)

Displayed \ Answered	A	B	C	D	E	F	G	H	nothing
A	20.0%	6.7%	3.3%	0.0%	0.0%	3.3%	0.0%	0.0%	66.7%
B	0.0%	16.7%	3.3%	3.3%	6.7%	0.0%	6.7%	3.3%	60.0%
C	6.7%	6.7%	3.3%	3.3%	0.0%	6.7%	0.0%	0.0%	73.3%
D	0.0%	0.0%	0.0%	0.0%	6.7%	0.0%	6.7%	6.7%	80.0%
E	0.0%	0.0%	6.7%	3.3%	3.3%	13.3%	3.3%	0.0%	70.0%
F	0.0%	0.0%	0.0%	0.0%	3.3%	23.3%	0.0%	0.0%	73.3%
G	0.0%	0.0%	3.3%	3.3%	3.3%	0.0%	3.3%	3.3%	83.3%
H	3.3%	3.3%	6.7%	0.0%	0.0%	6.7%	13.3%	3.3%	63.3%

Table 3. Confusion matrix containing the correct participant answers and the actual direction of rotation (anodic and cathodic stimulation)

Displayed \ Answered		Right	Left	nothing
Right	Anodic	70.0%	10.0%	20.0%
	Cathodic	10.0%	6.7%	83.3%
Left	Anodic	16.7%	66.7%	16.7%
	Cathodic	10.0%	13.3%	76.7%

4 Discussion

While many types of electro-tactile stimulation have used a bi-phasic pulse to prevent ionic problems, there are several studies that discuss the relationship between polarity and sensation threshold. Higashiyama et al. found that in the abdomen, forearm, and many other parts of the body, a cathodic pulse has a lower threshold than an anodic pulse [11]. On the contrary, Kaczmarek et al. found that in fingertip electro-tactile stimulation, an anodic pulse had a lower threshold [12]. This finding was confirmed by a primate nerve recording study [13]. Kajimoto et al. observed that the quality of the sensation was affected by the polarity, indicating selective nerve stimulation of the Meissner corpuscle by anodic stimulation and Merkel cells by cathodic stimulation [14]. In summary, previous research suggests that fingerpad stimulation has a lower threshold during anodic stimulation than does cathodic stimulation, while most other body parts have a lower threshold during cathodic stimulation than during anodic stimulation.

Contrary to previous research, we found that during underwater electro-tactile stimulation of the forearm, anodic stimulation produced a stronger sensation than cathodic stimulation, This is similar to findings regarding fingerpad stimulation. As the majority of answers during cathodic stimulation were "I felt nothing", our result is likely due to a difference in the sensation threshold, rather than a difference in the sensation quality. One possible explanation is that while the fingerpad have much thicker skin (horny layer) than other body parts, water may play a similar role to the thick skin layer during underwater electro-tactile stimulation. However, the underlying mechanisms of this phenomenon needs to be further explored.

In anodic stimulation, most participants were able to identify the direction of stimulation and the direction of rotation. However, the correct answer rate was not particularly high. We suppose that this is partly due to the different thresholds among the electrodes, since we set the current amplitude to be constant. In the future we plan to adjust the amplitude of each electrode.

5 Conclusions

As a first investigation of the potential use of underwater electro-tactile stimulation for in-bath entertainment, we investigated the ability of participants to localize the simulation and identify the polarity of the stimulation. We found that anodic stimulation produced a stronger sensation than cathodic stimulation when used for underwater electro-tactile stimulation. Furthermore, the participants were able to identify the direction of the tactile stimulation and the direction of rotation of the anodic stimulation.

Our future work includes automatic adjustments of electrical stimulation in accordance with real time position sensing. Furthermore, we plan to develop applications of in-bath entertainment by combining tactile stimulation with images and sound.

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