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Evaluation of the possibility and response characteristics of laser-induced tactile sensation

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HIGHLIGHTS

- Laser-induced tactile sensation on the fingertip was examined.
- Laser energy affect the possibility and response characteristics of tactile sensation.
- Precision and specificity were high but, accuracy and sensitivity were not high.
- Laser energy density is positively correlated with tactile perception.

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ABSTRACT

In this study, we examined the possibility and perceptual response characteristics of tactile sense induced by laser stimulation to the finger with different laser energy densities through human response experiments. 15 healthy adult males and 4 healthy adult females with an age of 22.6 ± 2.2 years were tested. A frequency-doubled Q-switched laser was used with a wavelength of 532 nm and a 5 ns pulse width. The experimental trial spanned a total of 30 s and included a rest phase (19 s), a stimulation phase (7 s), and a response phase (4 s). During the rest phase, subjects kept their fingers comfortable. During the stimulation phase, one of three types of laser energy density (13.5, 16.6, 19.8 mJ/cm^2) or a sham stimulation was used to irradiate the distal phalanx on the right index finger. During the response phase, the cognitive response to the laser stimulation was recorded by a PC by pressing the response button. The confusion matrix was configured to evaluate the possibility that the tactile sense was caused by the laser. In addition, changes in the response characteristics were observed according to three types of laser energy densities. From the analysis of the confusion matrix, the accuracy and sensitivity were not high. In contrast, precision and specificity were found to be high. Furthermore, there was a strong positive correlation between the laser irradiation and tactile perception, indicating that tactile sense can be induced using a laser in a mid-air manner. In addition, it was found that as the laser energy density increased, the tactile perception possibility also increased.

1. Introduction

Information presentation technology and interaction technology based on visual and auditory senses have changed human life dramatically. As these technologies developed and user requirements increased, haptics technology using tactile sense was introduced and applied to the existing visual and auditory interface. These have found corresponding applications in numerous fields associated with daily life [1,2]. At present, in order to implement three types of tactile sense, such as vibrotactile, pressure sense, and

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thermal sense, several methods are used, such as motor [3], piezo element [4], bimetal [5], electromagnetic [6], cuff [7], peltier element [8], and others. These methods can elicit a tactile sense only when they are in contact with the skin. Recently, the use of the immersive interface, emphasizing the user experience (UX), has been increasing in augmented reality or in 3- or 4-Dimensional interaction systems. The contact method accompanying the actuator and the control system that presents the tactile sense in such a system is somewhat unsatisfactory in terms of its user-friendliness. Therefore, to ameliorate the limitations of contact manner, methods have been developed using focused ultrasound [9,10], and a tactile device of the non-contact type with tight vortices of air [11,12]. However, these methods have similar problems in that the working distance available to deliver the effective tactile sense is short (approximately 50 cm or less), and unwanted sound is caused in a number of ultrasound transducers and air compressors. In particular, in the case of the method that uses air, the spatial resolution is low, approximately 80 mm or more, and an additional tactile sense called feel-cold occurs.

Laser is extensively used in industrial, medical, and military fields because it can easily adjust the irradiation energy and tightly transfer the energy to one or more focused spots at long distances. One of the various effects elicited from the use of a pulsed laser, the photomechanical effect is especially used, mainly in the ablation area causing damage to the target object [13–15]. However, if the magnitude of the pulse energy and the pulse duration are adjusted properly, a stress wave can be generated by the photomechanical effect without causing damage to the object [16–19]. This is the phenomenon according to which laser energy is absorbed in the elastic medium within a short time period, and where mechanical pressure occurs owing to thermal expansion. Recently, an attempt to use this phenomenon has been reported in order to induce tactile sensation [18,19]. Specifically, it has been reported that the characteristics of laser that transfer mechanical pressure at a high spatial resolution from a distance and in a mid-air manner can be used to overcome the limitations of the existing non-contact tactile sense displaying methods. However, in order to actually use the laser-based tactile sense presentation technology, additional studies will be needed. Particularly, the possibility of the tactile sensation caused by laser stimulation should be evaluated, and the perception and cognitive characteristics of tactile sense depending on various parameters, such as the laser energy density, wavelength, spot size, repetition rate, etc., should be studied.

This study evaluates the possibility of the laser-induced tactile sensation by laser stimulation, and observes the response characteristics depending on the changes in laser energy densities. Three types of laser energy that can induce tactile sense are pulsed to the distal phalanx on the right index finger, and the analysis of the characteristics of tactile perception is performed through the human response experiment.

2. Methods

2.1. Participants

Fifteen healthy males and four healthy females with an age of 22.6 ± 2.2 years college students participated in this study. They were also confirmed to be right handed based on the Edinburgh Handedness Inventory test [20]. None of the participants were reported to have a history of psychiatric or neurological disorders. The overall procedure was explained to all subjects who signed a consent form for the procedure. This study was approved by the institutional review board at Chosun University, Gwangju, in the Republic of Korea (IRB-13-008).

2.2. Experimental setup

The setup used for the laser-induced tactile perception experiment is shown in Fig. 1(a). The laser system used was a frequency-doubled Q-switched laser (Brilliant B, Quantel, USA) operating at a wavelength of 532 nm and with a 5 ns pulse width. The laser beam was pulsed to the palm side of the distal phalanx on the right index finger of the subjects through optical density (OD = 0.4) filters and lens (Fig. 1(b)). The spot diameter ($1/e$) on the finger surface was set at 0.48 mm by adjusting the plano-convex lens (f = 15 cm). Laser energies of 1.3 mJ, 1.6 mJ, and 1.9 mJ, were pulsed. The maximum energy of 1.9 mJ used in this study also constituted a parameter used in a previous study [18,19] to induce a tactile sense. At this time, the energy densities over the limiting aperture for the specific laser energies and spot sizes were 13.5, 16.6, and 19.8 mJ/cm^2, respectively. All of these energies and densities were less than the maximum permissible exposure (MPE) level, and they are thus considered safe for the skin [21]. Subjects were pressed the response button with their left hand to record the feeling after the laser stimulation (Fig. 1(b)). To cancel the auditory and visual factors, all subjects wore a headset in which white noise was playing, and the light when the laser was irradiated was blocked by a black curtain. A custom-made trigger module generated a trigger signal under the command of the PC. This signal was transmitted to the laser system to pulse the laser. The normal operation of the system was verified through a bi-directional data communication link with the PC, using a USB connector (Fig. 1(a)).

2.3. Experimental design

One trial of the experiment was composed of a total period of 30 s, including a rest phase (19 s), a stimulation phase (7 s), and a response phase (4 s) (Fig. 2). During the rest phase, subjects kept their finger comfortable after a "rest" voice was heard through the headset. During the stimulation phase, stimulation was presented to the skin by the pulsed laser. Four seconds before the presentation of the stimulus, a "ready" voice instructed the subjects, and they were then asked to move their finger to the stimulation position and maintain a steady state for 3 s after the presentation of the stimulation. During the response phase, the cognitive response to the stimulation was recorded on the PC by pressing the response button. This phase occurred after the "beep" sound was heard, and any response after 4 s was ignored. Button "1" was previously defined to denote the "no feeling" state, button "2" the "tactile sense", and button "3" the state where "pain" was elicited. The tactile sense was defined as the concept that included all the "hard," "soft," "firm," "slippery," and "tingling" sensations reported as feelings induced by laser stimulation except for pain through the previous experiment. Three types of laser energy (1.3 mJ, 1.6 mJ, and 1.9 mJ) were pulsed for five trials each, and sham stimulation was performed without an actual laser pulse for an additional five trials. Therefore, a total of 20 trials of actual laser stimulations consisting of 15 trials (three types of laser energy × five trials) and five sham stimulation trials were carried out in one session. In order to eliminate the repetition effect and carryover effect, the trial was performed in a random order and was repeated three times for each participant. Thus, the total number of responses was 19 (people) × 20 (trials/session) × 3 (sessions) = 1140. The times taken by each phase, voice, response data recordings (as a text file), trigger signal, and other parameters were controlled by custom-made software installed on the PC.

2.4. Data analysis

In order to evaluate the possibility of tactile sense induced by laser stimulation, the confusion matrix was configured. This method is commonly used when classifying parameters into a