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Distinct Pseudo-Attraction Force Sensation by a Thumb-Sized Vibrator that Oscillates Asymmetrically

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Abstract. This paper describes the development of a thumb-sized force display for experiencing a kinesthetic illusory sensation of being continuously pushed or pulled. We previously succeeded in creating a sensation of being pulled with a prototype based on a crank-slider mechanism, but recently we did so with a thumb-sized actuator that oscillates asymmetrically. With this tiny and light force display, the directed force sensation is perceived just as strongly as with the previous larger prototypes. We conducted a user study using the method of paired comparisons. The results show that a specific vibrator with a 7-ms pulse at 40 Hz induces the sensation most clearly and effectively.

Keywords: Sensory illusion · Perception · Asymmetric oscillation · Mobile device · Vibration

1 Introduction

The increase in mobile and wearable devices equipped with global positioning sensors has boosted their use for pedestrian navigation or city wayfinding. However, displays for pedestrian navigation are currently constrained to providing audiovisual and simple vibrotactile cues. Therefore, users usually have to fixate on a small map on the screens of their mobile devices to obtain helpful information. One of the easiest and most intuitive ways to give directions without the need to pay attention to a map is to help users turn in the direction they should be facing. A display creating a directed force sensation enables the user to promptly understand the presented direction since haptic stimuli are fundamentally directional.

Over the past years, we have been refining a method to create a sensory illusion of being pulled and have developed various ungrounded force displays to create a sensation. Since it is impossible to create a continuous translational force sensation without an external fulcrum, our method of exploiting the characteristics of human perception is the only way to create a translational force sensation in mobile devices. The user does not feel the discrete simple vibrating sensation that is so common in conventional mobile devices today. Instead, the user feels a smooth sensation of being pulled, akin to what we feel when someone leads us by the hand. However, since our previous prototypes were based on mechanical linkages, they were too large and heavy to be applied to mobile devices.

In this paper, we introduce a new tiny but mighty force display. For all users, the haptic or somatosensory cues created by the developed force display are, like lead-by-hand navigation, intuitive in indicating a certain direction.

2 Our Approach

We have been developing translational force displays utilizing the nonlinearity of human perception since 2004 [1], and since then many approaches have been proposed and aggressively studied [6,9–11,13]. Our approach to creating a sensation of being pulled exploits the characteristics of human perception, using different acceleration patterns for the two directions to create a perceived force imbalance. A brief and strong force is generated in a desired direction (e.g., leftward), while a weaker one is generated over a longer period of time in the reverse direction (e.g., rightward). Although the average magnitudes of the two forces are the same, reducing the magnitude of the longer and weaker force to below a sensory threshold makes the holders feel as if they are being pulled to the desired direction (e.g., leftward). This force perception would be determined by a complex sensory input from the skin, joints and muscles. We fabricated a prototype consisting of a crank-slider mechanism to create an illusory sensation of force.

Nakamura and Fukui proposed an actuator, consisting of two eccentric masses attached to two motors' shafts, to generate an illusory sensation of force [9]. Rekimoto proposed a similar device using a commercially available vibrator (Force Reactor L-type; ALPS Inc.) [10]. Rekimoto used the cycle of 2 ms (ON) and 6 ms (OFF) for producing a force sensation, whose net cycle is virtually 125 Hz, or the pulse width corresponds to 250 Hz. Although a complex sensory input from not only cutaneous corpuscles but also those in tendons and muscles would creates the force perception as we address above, these frequency ranges maximize the response of Pacinian corpuscles on the glabrous skin [8]. The Pacinian corpuscles are sensitive to vibration at 100–300 Hz and are thought to detect vibration. In contrast, Meissner corpuscles, which detect slip, are most sensitive in the frequency range of from approximately 5 to 40 Hz [7,12], which is thought to detect vibration. The strong response of Pacinian corpuscles may make it difficult to discriminate differences in the symmetric vibration and the asymmetric acceleration change. If we use asymmetrically oscillating stimuli that selectively stimulate the Meissner corpuscles, not the Pacinian, the force sensation of being pulled will be more clearly perceived.

In this paper, we compare the perceptual characteristics using asymmetrically oscillating stimuli whose net frequency and pulse width are different.

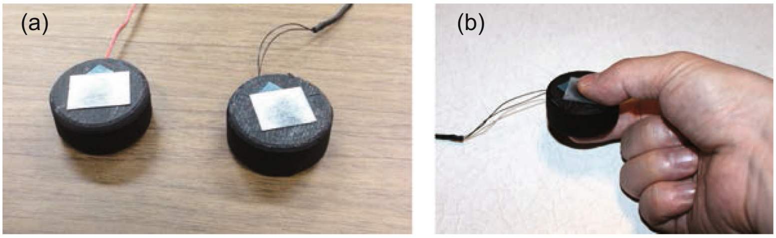

Fig. 1. (a) Two different actuators covered with cylinders having the same shape used in the experiment. (b) How the cylinder was pinched in the experiment.

3 Evaluation

3.1 Method

Participants. Participants: We conducted an evaluation to compare combinations of pulse durations and actuators. Nine volunteer right-handed subjects, ranging from 25 to 49 years of age (seven males and two females, average 33.8 years, SD 7.1 years), participated in the experiment. They had no known tactile or kinesthetic sensory system abnormalities. This research was approved by the local ethics committee.

Apparatus and Stimulus. Here, we selected two linearly vibrating actuators (Force Reactor L-type, ALPS; Haptuator, Tactile Labs.). Each actuator was covered with a cylinder whose size is ϕ 40 mm × 17 mm (Fig. 1), which are made of ABS resin. A piece of a sand paper (#1000 grit) was pasted on its surface to control the surface roughness. The pulse duration cycle was 2 ms: 6 ms or 7 ms: 18 ms. The combination of 2 ms: 6 ms and the Force Reactor is identical to that in a previous report [10]. The duration cycle of 7 ms: 18 ms was selected from the result of a pilot study, which maximized the perceptual amplitude of the force sensation of being pulled. We used the same amplifier gain.

A stimulus was created by pairing a pulse duration cycle with an actuator. Figures 2 and 3 show acceleration patterns of the four combinations used in the experiment. Vibrations of the force display when an experimenter held it were recorded with a laser sensor (LK-G150, Keyence Inc.) at 20 kHz and smoothed using a fifth-order, zero phase lag, low-pass Butterworth filter with a cutoff frequency of 1 kHz. We then calculated the acceleration from the acquired position data.

The direction of the stimulus was lateral to the body (left-right direction) and switched every one second in a trial. The stimulus was presented for four seconds. The order of the pulse duration was also randomized.

Procedure. A trial consisted of two four-second stimulus intervals presented sequentially. An experimenter handed one of the two cylinders to a seated participant. The participants pinched the cylinder on the top and bottom using the

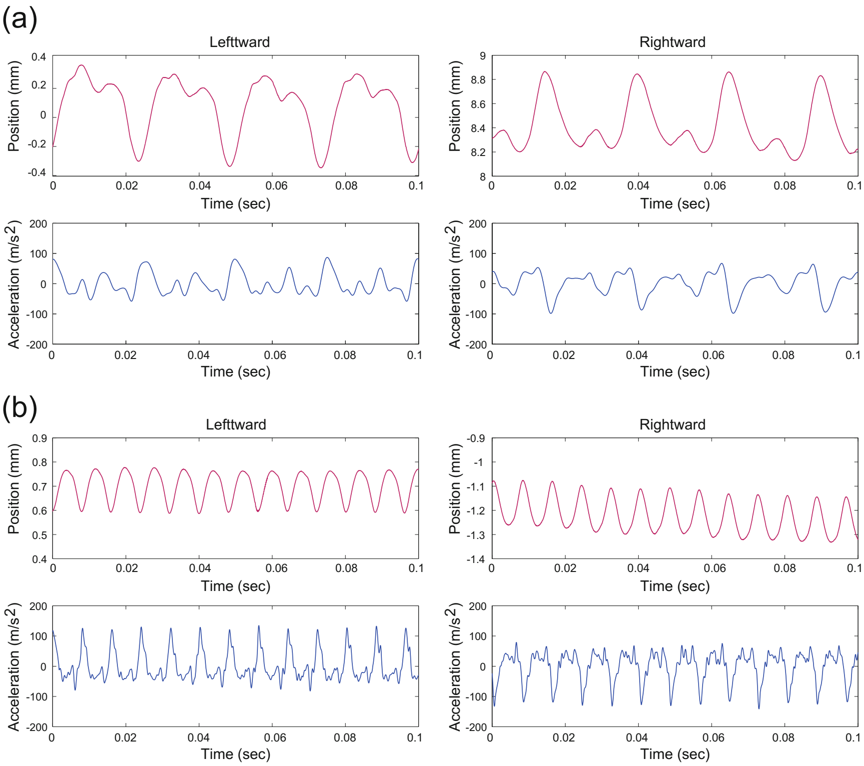

Fig. 2. Acceleration pattern of the four combinations used in the experiment. (a) Haptuator with 7 ms: 18 ms (the net cycle is virtually 40 Hz). (b) Haptuator with 2 ms: 6 ms (the net cycle is 125 Hz).

thumb and index finger of the dominant hand (right hand). They were allowed to move their arms and hands freely. After they had received instructions from the experimenter, the participants felt a vibration for four seconds. Then, the cylinder was changed by the experimenter. The participants pinched it and felt a vibration in the second interval. Participants reported which of the two intervals contained the stimulus inducing a clearer force sensation. In other words, we adopted the Thurstone's method of paired comparisons to find the stimulus that induces the force sensation the most clearly.

They experienced 2 actuators × 2 pulse duration cycle × 2 times (counterbalanced order). The participant was given about a 30-second break after every trial to reduce the effect of fatigue or sensory adaptation due to vibration. No feedback was given regarding their judgments. Visual input was suppressed by having the participants close their eyes during the experiment.

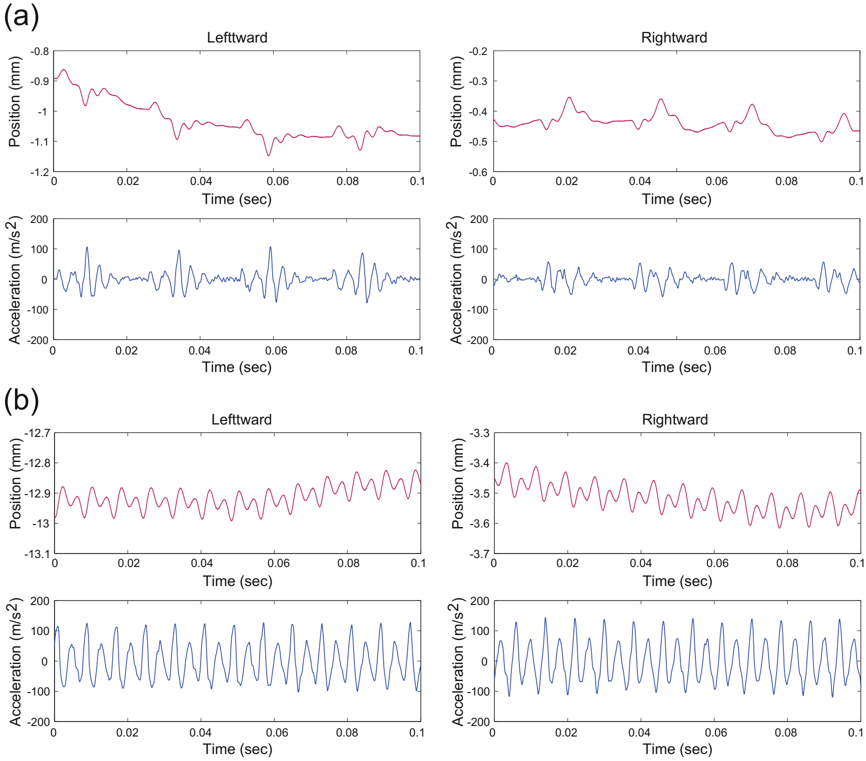

Fig. 3. Acceleration pattern of the four combinations used in the experiment. (a) Force Reactor L-type with 7 ms: 18 ms (the net cycle is virtually 40 Hz). (b) Force Reactor L-type with 2 ms: 6 ms (the net cycle is 125 Hz).

3.2 Result and Discussion

Figure 4 shows the scale values of the clarity of the force sensation. In this scale, on the basis of the average proportion of times a combination was chosen as the stimulus inducing a clearer force sensation, the combinations were ordered along a continuum to represent the degree of clarity of force sensation. For all four combinations (2 actuators × 2 pulse duration cycle), the combination of the Haptuator and the pulse duration of 7 ms: 18 ms was judged to create the clearest force sensation. In contrast, there were no differences between the Force Reactor with 2 ms: 6 ms [10] and Haptuator with 2 ms: 6 ms, both of which induced less clear force sensation than the Haptuator with 7 ms: 18 ms. Finally, the Force Reactor with 7 ms: 18 ms created the least clear sensation.

Interestingly, the conditions with the duration of 7 ms: 18 ms were judged to be both the best and the worst, indicating that the combination of the actuator and duration seems to be an important factor for inducing a clear force sensation. We speculate that this is due to the natural frequency of the actuators. The natural frequency of the Haptuator is about 60 Hz [14], and that of the Force

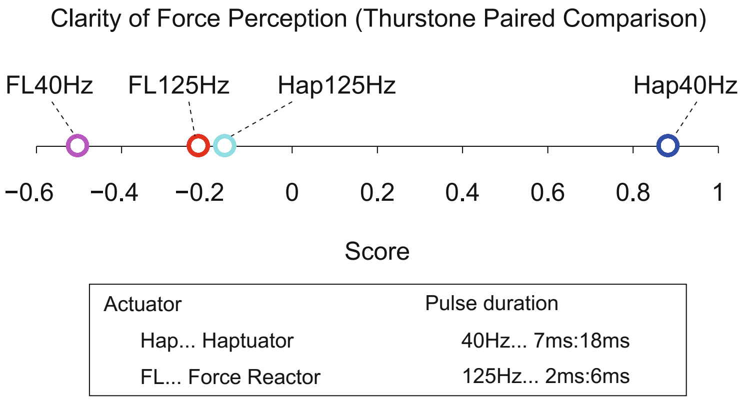

Fig. 4. Result of paired comparison.

Reactor is about 250 Hz, albeit both of them were not the resonant one of the system including two fingers. On the other hand, the half cycle of 70 Hz is close to 7 ms and that of 250 Hz is close to 2 ms. Therefore, the results for the Haptuator with a 7-ms pulse and the Force Reactor with a 2-ms pulse were better than for the other combinations.

All participants reported that they felt a strong illusory force sensation of being pulled in both directions with the Haptuator in the 7 ms: 18 ms condition. Some participants pointed out that only one direction (e.g., only rightward) was clear with the Haptuator in the 2 ms: 6 ms condition. There were no significant differences among the tendency of the participants' judges ($\chi^2(40) = 25.5$, $p = 0.96$).

4 Implementation

4.1 Thumb-Sized Force Display

On the basis of the results of the experiment, we fabricated two prototypes: a one-DoF force display [Fig. 5(a)] and a two-DoF force display [Fig. 5(b)]. The size of the one-DoF force display is greatly decreased by 95 % (to $18 \times 18 \times 37\,\text{mm}^3$) compared to the earlier one [2,4], and its weight is greatly decreased by 90 % (to 25 g). With this tiny and light force display, almost all people who have experienced subjectively reported that the directed force sensation is perceived just as strongly as with the previous larger prototypes [3,5].

We have adopted the Haptuator as the actuator, and a microcontroller board (PIC18F2550) is connected to an amplifier unit to drive the actuators.

4.2 Application

Figure 6 shows examples of applications using the thumb-sized force display. With a motion tracking system, the amplitude and direction of the force sensation are altered according to the user's hand position while the user pinches the

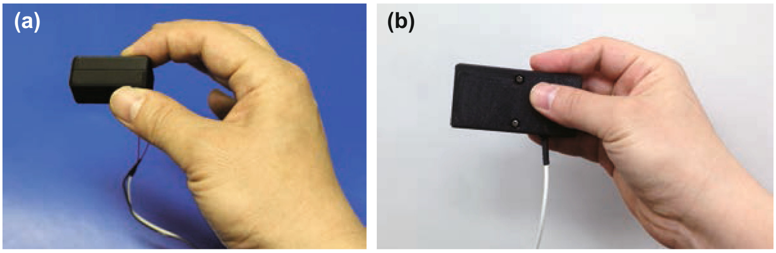

Fig. 5. Proposed novel thumb-sized (a) one-DoF and (b) two-DoF force displays.

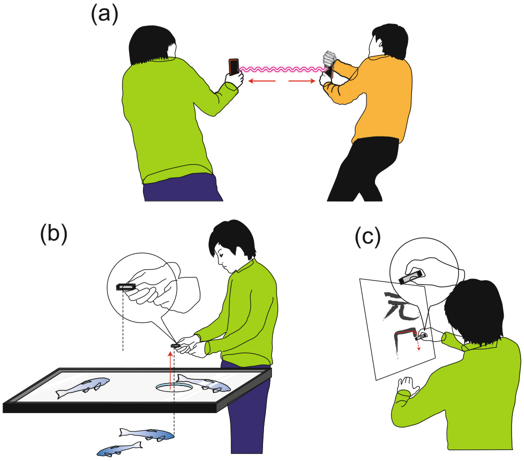

Fig. 6. Application examples using thumb-sized mobile force display. (a) Tug-of-war. (b) Angling game. (c) Calligraphy guidance.

thumb-sized force display. If we use two or more force displays, multiple users can experience the tug-of-war application together [Fig. 6(a)]. In the angling game, users can feel a sensation of a nibble on the hook and being pulled with no fishing lines [Fig. 6(b)]. In addition, users can learn calligraphy with the thumb-sized force display [Fig. 6(c)]. These devices can of course be used to support visually impaired people in finding their way [5,6].

5 Conclusion

We reported a novel approach for creating the sensation of being pulled or pushed, and we examined the pulse pattern that is clearly felt for participants using two vibrators. We have shown experimentally that the combination of a Haptuator with 7 ms: 18 ms pulse duration cycle induced the clearest sensation. On the basis of the results of the experiment, we developed a thumb-sized force display for experiencing a kinesthetic illusory sensation of being continuously pushed or pulled. These findings can provide valuable insights into the design of mobile force displays.

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