Directed Force Perception When Holding a Nongrounding Force Display in the Air

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Abstract

We have proposed a novel force perception method for mobile and wearable use. The method is based on the nonlinear relationship between perceived acceleration and physical acceleration; rapid acceleration translates to a stronger sensation, and slow acceleration to a weaker one. A prototype of the haptic display based on the method generates uni-directional force sensation using a crank-slider mechanism that physically generates bi-directional force. In the mechanism, motion of linkages, called the swinging force, makes it difficult for users to distinguish between simple vibration and directed force. An experiment was performed to clarify the effect of the swinging force when subjects held the display in the air. The results show that the angular resolution with which the force direction can be discriminated was significantly smaller with an antiphase tandem pair of force displays designed to counteract it than with an inphase pair designed to double it. This indicates that the directed force sensation is effectively perceived by being limited the translational motion.

Keywords: interface using sensory illusion, perception, asymmetric acceleration

1 Introduction

Most force feedback devices have to use either mechanical linkage to establish a fulcrum relative the ground [1][2] or huge air compressors [3], or demand the wearing of a heavy device [4]. None of them can be used freely outside the laboratory. Although some wearable and mobile force displays have been proposed, they can produce neither constant force nor translational force, without also producing reaction force. Examples include GyroDisplay[5], which utilizes the gyro effect, and GyroCube[6], which presents torque using the change in angular momentum of a motor; they can generate only short-time rotational force since they use a change in angular momentum.

We have proposed a novel force perception method [7][8] that can generate both temporal-stable and translational force sensation. In our method, brief intense pulses of acceleration alternate with longer periods of low-amplitude recovery. Although the net acceleration is zero, humans perceived a net force sensation in the direction of the pulses. This is attributed to the nonlinear relationship between perceived acceleration and physical acceleration. We built a prototype handheld force display to generate a periodic motion with the asymmetric acceleration based on the method using a crank-slider mechanism (Fig. 1). Experimental results have shown that the virtual force vector can be effectively perceived at around 10 Hz of rotational frequency of the motor when the force display fixed on a linear slider was held [8].

In this paper, we examine the characteristics of the force perception, into which an asymmetric acceleration is perceptually translated, when the force display without the slider is held in the air.

2 Preliminary experiment: Describe what you feel when holding the display

We conducted a pilot study in which the force display was held in the air. We asked naive subjects to describe in words or drawings what they felt when holding the display. The subjects were not given any explanation about the principle.

2.1 Method

2.1.1 Participants

Twenty-two subjects (twenty right-handed men and two right-handed women, aged 20-39 years) participated. All subjects were naive to the objectives of the experiment. None of the subjects reported any known tactual impairments of their hands. Visual and auditory effects were not suppressed; subjects could see whether the force display was in action or not.

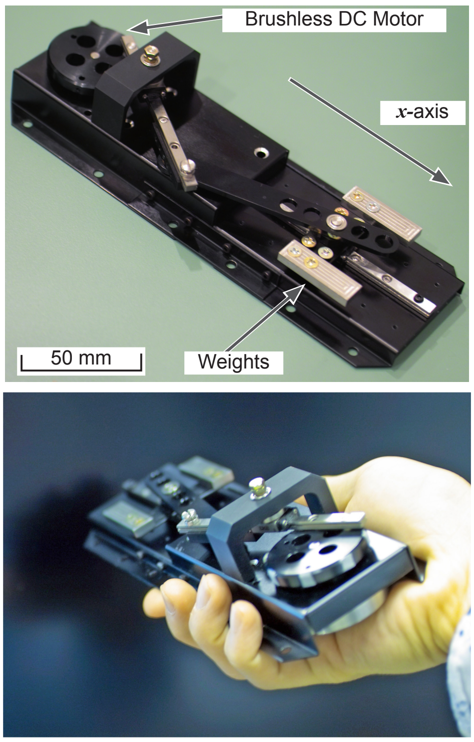

Figure 1: *Phorographs showing the force display utilizing the nonlinearity of human perception (top) and how it is held (bottom).*

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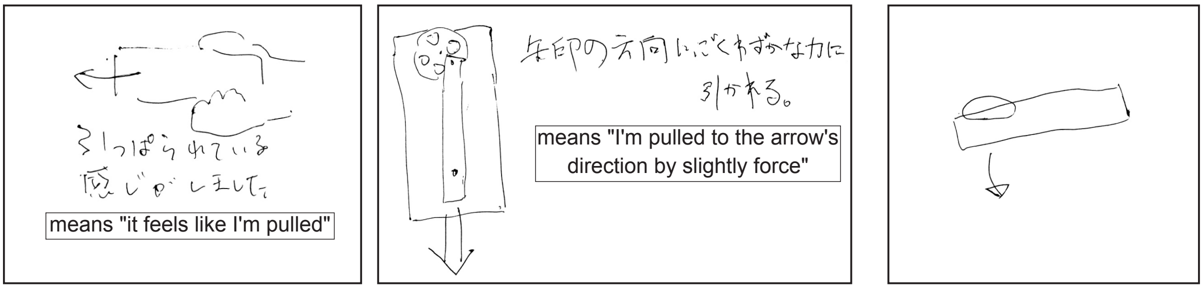


(a) female, right-handed, 28 years of age *(b) male, right-handed, 21 years of age* *(c) male, right-handed, 36 years of age*

Figure 2: *Drawings showing how subjects feel without explanation about the force display. Drawings (a) and (b) indicate as a kind of directed force sensation was perceived. In (c), the subject felt that the weight of the device changed.*

2.1.2 Apparatus

The experimental system consists of the force display (Fig. 1.), a power-supply circuit, and a motor amplifier (DEC50/5; Maxon Motor). The motor in the virtual force display is a brushless DC motor (EC45 Flat motor; Maxon Motor), which has a power rating of 30 W and weighs 88 g. The rotational frequency of the motor was controlled by a one-chip microcomputer (PIC18F252; Microchip Technology Inc.) and a 12-bit D/A converter. The motor's power supply was DC 18 V. The weight of the force display held by subjects weighed approximately 230 g. The total reciprocating mass in the force display was 20 g.

2.1.3 Procedure

Subjects held the force display without any explanation other than to hold it and say what they felt. First, the subject held it to present pulling or pushing force. The stimulation started after the experimenter's instruction. Next, the subject shifted it to the opposite direction. The subject held it with the dominant hand (right hand, in this case). Subjects were instructed how to grasp the display with aid of a photograph showing the display held with the right hand. The subjects were asked not to squeeze the display, (but to grasp it with just enough strength to keep it from slipping from the hand). The rotational frequency of the motor in the force display was 10 Hz, which is the one of the most effective frequencies for perceiving the force sensation [8]. Stimulus duration was about 10 seconds. Subjects were standing and their elbow was not fixed. Correct-answer feedback was not provided during the experiment.

2.2 Results

Fifteen out of 22 subjects reported a feeling of being pulled without prompting. Comments were as follows:

"It feels like it's pulling me."

"Apparently, I was drawn to one direction as if the display was falling down from my hand. I felt strong if I held softly."

"I felt like I was pulled forward."

"First my hand was pulled. After the display turning over, my hand was pushed."

"Feeling of pushing or pulling."

"Felt as if I was taken away."

Seven out of 22 subjects reported it made no sense without prompting. Comments included:

"It is vibrating. There is no impression of change, though I was asked to shift the direction of display."

"I did not feel any difference."

Figure 2 shows examples of pictures drawn by the subjects. Most of the subjects perceived a directed force sensation. However, some said it was only vibration or that the weight of the display had changed.

3 Discussion of the preliminary experiment

Here, we will analyze the motion of the proposed display when it is nongrounding in order to determine the cause of misperception.

The position of the reciprocating slider (slider *e* in Figure 3) in *x*-coordinate can be expressed by

$$x = r\cos\theta + \mu(d - r\cos\theta) + \sqrt{l_2^2 - \{r(\mu-1)\sin\theta\}^2} \tag{1}$$

where

$$\mu = \frac{l_1}{\sqrt{r^2 + d^2 - 2rd\cos\theta}}, \tag{2}$$

x = OD, r = OB, d = OA, l_1 = BC, l_2 = CD, and θ =AOB in Figure 3.

In the y-coordinate, position of point C in Figure 3 can be expressed by

$$y = r(\mu - 1)\sin\theta. \tag{3}$$

The absolute value, F_{com}, is given by

$$F_{com} = \sqrt{\left(m_x \frac{d^2x}{dt^2}\right)^2 + \left(m_y \frac{d^2y}{dt^2}\right)^2} \tag{4}$$

where m_x represents the total weight of equivalent reciprocating objects, and m_y represents the total weight of equivalent moving objects in the orthogonal direction. The direction of resultant force, ϕ, is given by

$$\phi = \begin{cases} \arctan\left(\dfrac{m_y \frac{d^2y}{dt^2}}{m_x \frac{d^2x}{dt^2}}\right), & \text{if } \dfrac{d^2x}{dt^2} > 0 \\ \arctan\left(\dfrac{m_y \frac{d^2y}{dt^2}}{m_x \frac{d^2x}{dt^2}}\right) + \pi, & \text{if } \dfrac{d^2x}{dt^2} < 0, \dfrac{d^2y}{dt^2} > 0 \\ \arctan\left(\dfrac{m_y \frac{d^2y}{dt^2}}{m_x \frac{d^2x}{dt^2}}\right) - \pi, & \text{if } \dfrac{d^2x}{dt^2} < 0, \dfrac{d^2y}{dt^2} < 0 \end{cases} \tag{5}$$

Display parameters were r = 15 mm, d = 29 mm, l_1 = 60 mm, l_2 = 70 mm, m_x=37.0 g, m_y=8.9 g†. Figure 4 shows (a) acceleration in the intended direction (x-axis), (b) acceleration in the unintended direction (y-axis), (c) the absolute value of the resultant force vector, and (d) the deflection angles between the resultant force vector and x-axis. Figure 5 shows the change of the resultant force vector by combining (c) and (d). Figure 5 reveals that the effect of the motion of the linkages on perception as a

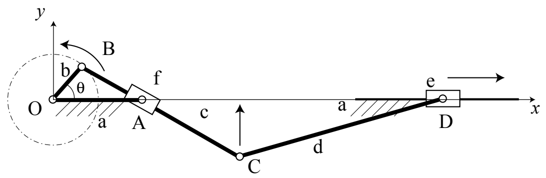
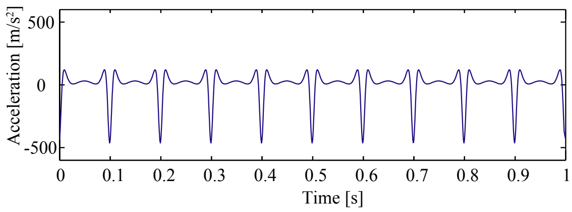
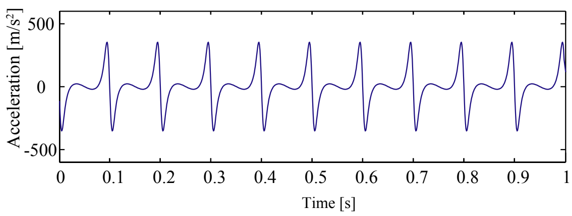


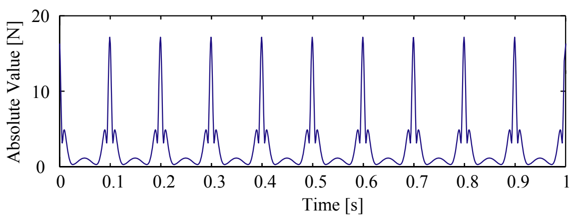
Figure 3: *Mechanical scematic of the force display*



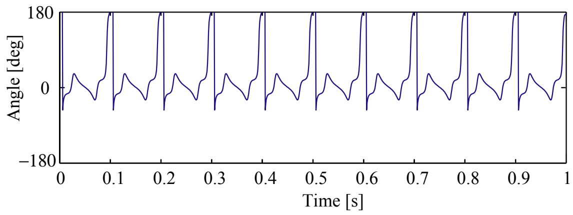
(a) Acceleration in x-axis



(b) Acceleration in y-axis



(c) Absolute value of resultant force (F_{com})



(d) Deflection angle of resultant force (ϕ)

Figure 4: *Characteristics of the force display when nongrounded. Frequency of the asymmetric acceleration is 10 Hz and the mass of the slider is 20 g.*

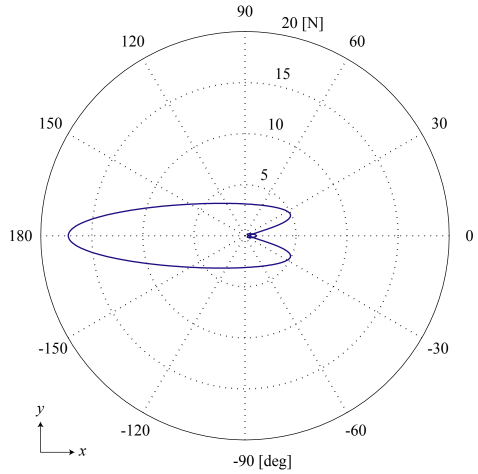


Figure 5: *Change of the resultant force vector. The force direction covers not merely the x-axis but also the y-axis. The mass of the slider is 20 g.*

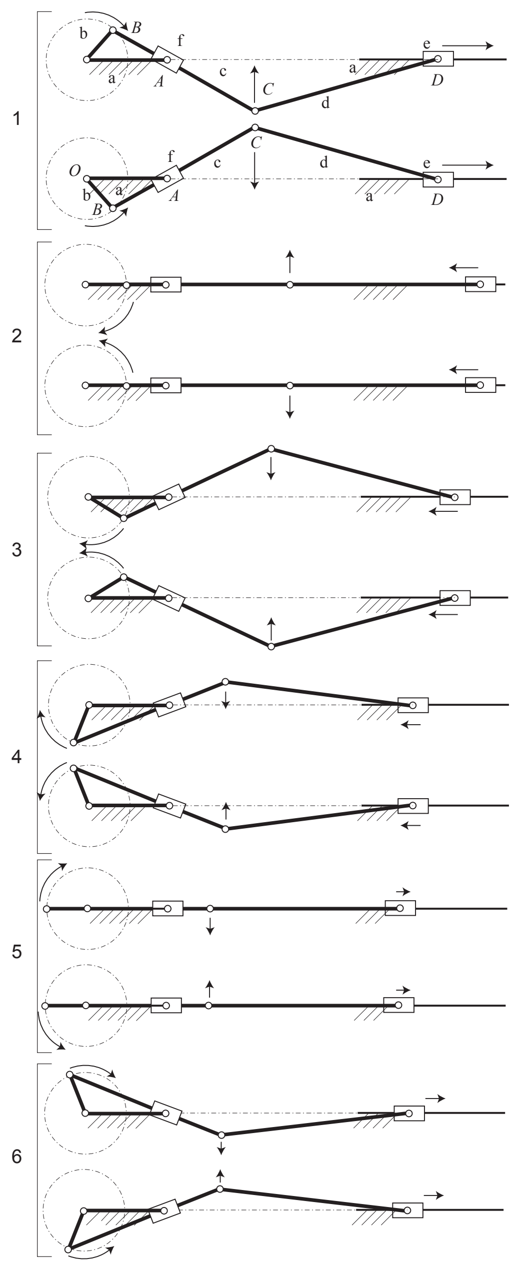


Figure 6: *Sequence of motion of an antiphase tandem pair. (1→2→3→4→5→6→1→...)*

† m_x and m_y were calculated as follows; the mass of weights on the slider is 20 g, that of linkage BC is 10.9 g, that of linkage CD is 6.5 g, and that of slider is 7.8 g. These is 100 %, 39 %, 84 %, and 100 % equivalent force in the x-direction, and 0 %, 52 %, 50 %, and 0 % equivalent force in the y-direction, respectively.

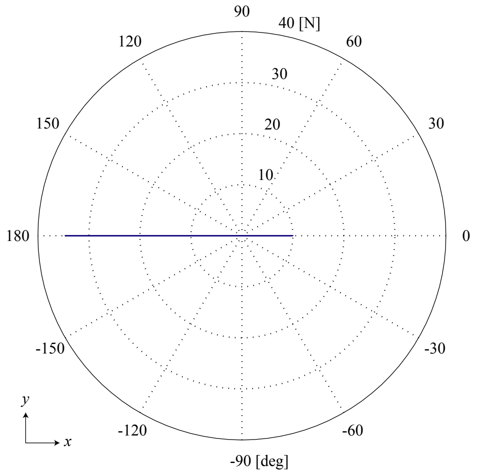


Figure 7: *Change in the resultant force vector with the antiphase tandem pair of the force displays. The direction of the resultant force vector is limitted to the x-axis. The mass of the slider is 40 g (20g each).*

unidirectional force sensation is not negligible. We think the force in the orthogonal direction (called swinging force) might lead to the sense of vibration.

To counteract the swinging force physically, we designed an antiphase tandem pair of the proposed crank-slider mechanisms (Fig. 6). In this mechanism, y-directional forces are always counterbalanced as shown in Fig. 7.

4 Comparison experiment: Counteracting the swinging force or not

In order to examine the effect of the swinging force, we determined the azimuth accuracy of the perceived force direction versus the stimulated direction generated by an asymmetric acceleration in the presence or absence of the swinging force by comparing two pairs of force displays (an antiphase and an inphase tandem pair) when each was held in the air.

4.1 Method

4.1.1 Participants

Four subjects (three right-handed men (MT, IT, GK) and one right-handed woman (AM), aged 25-29 years) participated in this experiment. Subjects IT, GK, and AM were experienced with the force display in pilot study. None of the subjects reported any known tactual impairments of their hands. None were involved in the research project nor knew the purpose of experiment.

4.1.2 Apparatus

Two sets of the force displays were arranged in two different phase-locked styles; an antiphase and an inphase tandem pair. One motor was driven in each pair. A stepper motor (E401; Astrosyn Inter Technology) was attached to a circular disk made of acrylate resin to establish pan motion. The specifications of the stepper motor were DC 9.6 V, two-phase, bipolar, and 1.8-degree step angle. The stepper motor was controlled by a one-chip microcomputer (PIC12F675; Microchip Technology Inc.) and a motor driver circuit, which provided micro-stepping (quarter) for high resolution. The step angle was controlled via a serial port in a PC. The holding torque of the stepper motor was 20 mNm. The stepper motor had a gear (module 1.0, 10 teeth), which was engaged with the gear made of acrylonitrile butadiene styrene (ABS) resin (module 1.0, 200 teeth). A pair of the force displays was fixated on the gear. The reduction ratio is 20. The total mass of the weights on the sliders in the force displays was 40 g. The total mass of the force display held by the subjects was approximately 1,240 g.

The "antiphase" pair was a tandem pair in which each crank rotated in the opposite direction as described in Section 3 and whose phases were mechanically locked using two spur gears [Fig. 8 (a)] such as Rhombic drive mechanism[9]. The module of the gears was 1.0, the number of teeth was 60, and the gear reduction ratio was 1.0.

The "inphase" pair was a tandem pair in which each crank rotated same direction whose phases were mechanically locked using two linkages [Fig. 8 (b)].

The antiphase pair eliminated the swinging force, and the inphase pair doubled it. The total mass of the pairs was adjusted to be equivalent. The rotation of motor was clockwise.

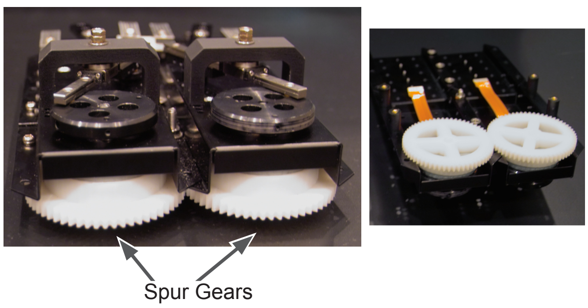
Figure 9 shows the experimental view and Figure 10 shows the experimental system configuration.

4.1.3 Stimuli

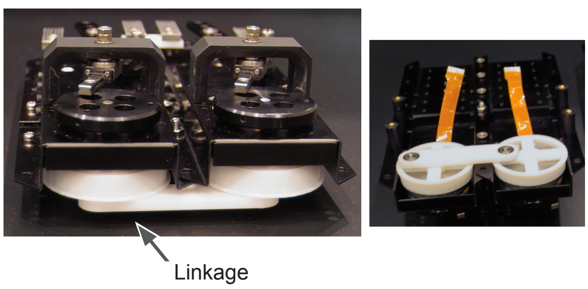
The haptic stimuli were generated by the two pairs of force displays. The orientation of the force vector was altered from 0 to 360° on the horizontal plane in 15° steps (24 vectors). Each vector was tested twice in an experimental session. The orientation was controlled by the stepper motor for each pair. The frequency of the asymmetric acceleration (rotational frequency of the motor) of 10 Hz was chosen so that the forces were clearly perceptible to all subjects. The stimulation was presented until the subjects had enough confidence.

4.1.4 Procedure

Subjects were seated in front of the force display and adjusted the height of the chair so that they could hold the device comfortably. Subjects instructed not to increase grip



(a) Antiphase pair



(b) Inphase pair

Figure 8: *Photographs of the pairs of the force displays*

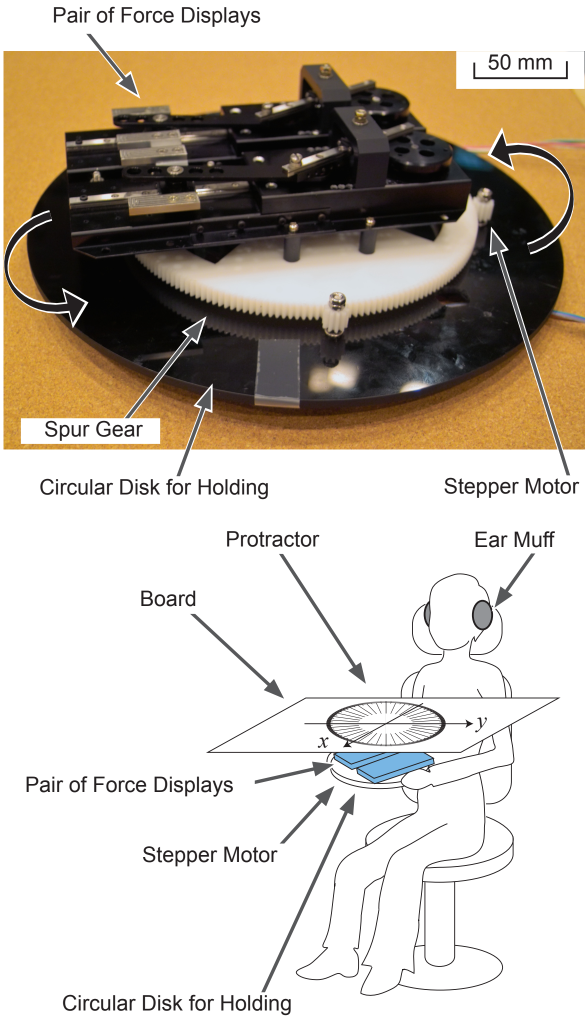


Figure 9: *Photograph of the experimental apparatus (top) and a sketch of the view (bottom).*

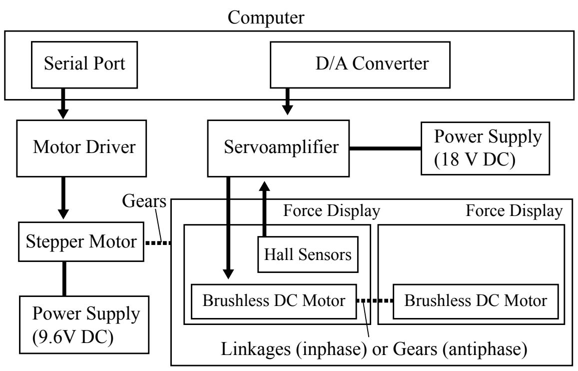


Figure 10: *Experimental system configuration.*

strength, to be relaxed. Auditory effects were suppressed by having them wear ear muffs (Optime II; PELTOR). The sequence of parameters was randomized for all subjects to reduce the order effect. The subjects were required to reply with one of 360 degrees; answers such as “I’m not sure” were not accepted. Subjects watched a circular protractor covering a circular disk in order to reply. The subject held the circular disk with both hands at a tape-marked place. The method of grasping the device was constant throughout the experiment. The arm and hand were not restrained. A board blocked the subjects' view of the apparatus and their hand. In order to remove the influence of adaptation by long-term vibration, the subject was given a two-minute break every ten trials. Pauses were allowed to avoid fatigue. The stepper motor rotated at least 180 degree in every trial. Correct-answer feedback was not provided during the experiment.

4.1.5 Data Analysis

The angular error is the angular difference between the orientation of the stimulus and that of the response.

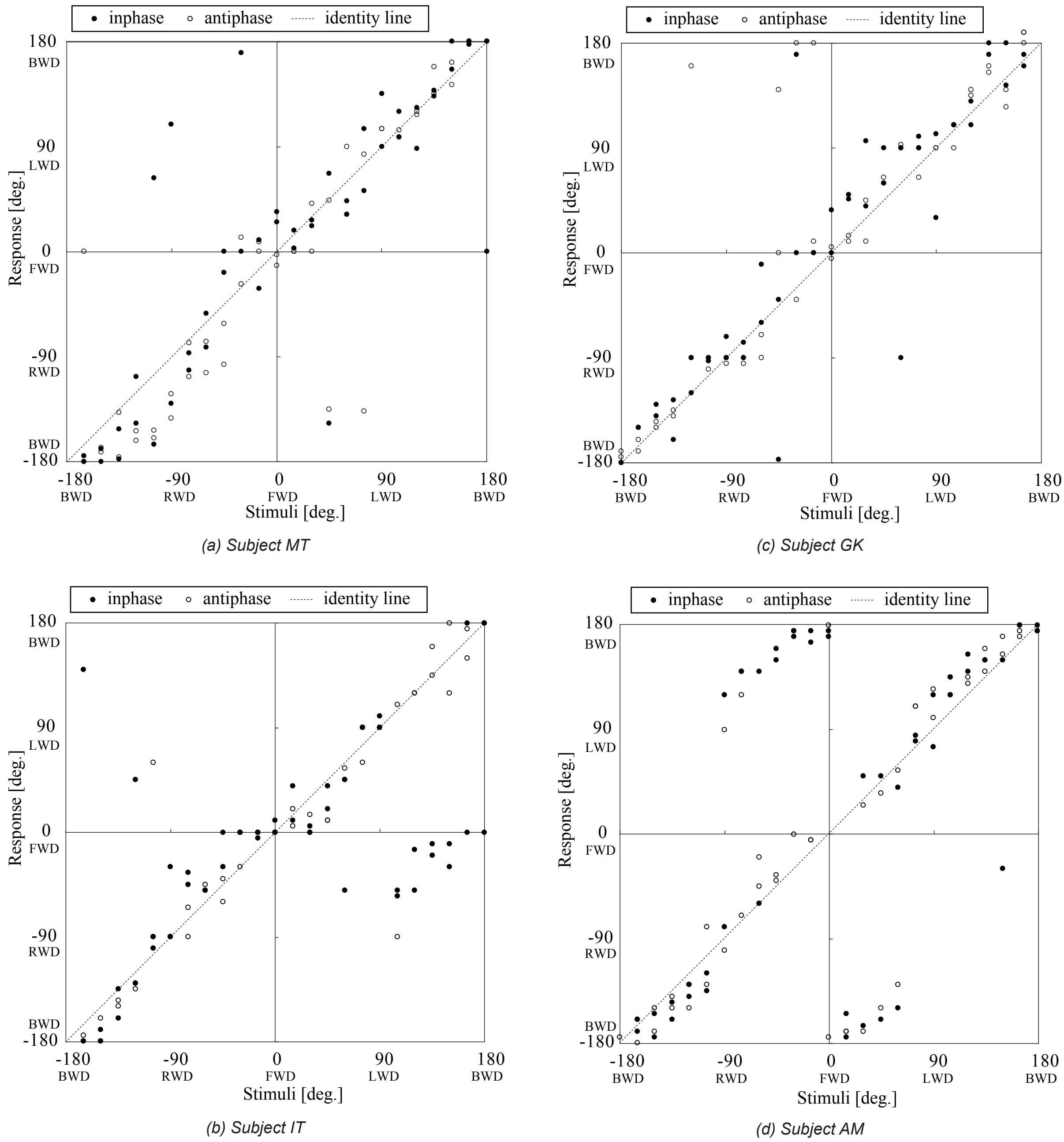
For each subject, we computed the root mean square (RMS) of angular errors to evaluate the deviation of all response. These angles were converted from 0 to 360 degrees into -180 to 180 degrees; forward is 0°, backward is ±180°, leftward is 90°, and rightward is -90°.

4.2 Results and discussion of Experiment

Figure 11 shows the experimental results for the four subjects. Data from the inphase tandem pair and antiphase tandem pair are shown by filled circles and open circles, respectively. The graphs indicate that a force sensation in almost all directions on the horizontal plane can be generated in each pair. In general, the responses were grouped around the identity line. However, some trials in which differences between responses and stimuli were around 180° were observed. The number of reverse-polarity trials in which the angular error was over ±90° in the antiphase tandem pair was smaller than that in the inphase tandem pair for all subjects. The average rates of straight-polarity trials for all subjects is 90.24 % for the antiphase pair, and 80.21 % for the inphase one ($t(3)=2.14$, $p<.10$), indicating that the force direction was better perceived using the antiphase tandem pair than the inphase one.

We hypothesize an isotropic force-direction sensitivity from a report that the systematic distortions are not present in the perception of force direction in horizontal plane [10]. In that case, the RMS of the angular errors is shown in Fig. 12. For all subjects except subject GK, the RMS of angular errors for the inphase pair were larger than that for the antiphase pair. We performed a paired *t*-test for the RMS of angular errors in the antiphase and the inphase tandem pair conditions. The results revealed that the RMS of the angular errors for the antiphase tandem pair was marginally significantly smaller than that for the inphase tandem pair ($t(3)=1.92$, $p<.10$), indicating that the force sensation was more precisely perceived using the antiphase tandem pair than the inphase one. This means the directed force sensation was susceptible to the effect of the swinging force.

Subject IT reported a clear pulling sensation with the antiphase tandem pair and unclear one with the inphase one. Subject GK reported that the antiphase tandem pair was efficient to perceive the directed force. Subject AM reported that the antiphase tandem pair was lighter than the inphase one and the pulse in the antiphase tandem pair was effectively felt. Subject MT reported that the force sensations using the inphase tandem pair were obscure especially leftward and rightward, but that they were clear with the antiphase one in those directions, adding that nevertheless the force sensations were weaker with the antiphase one. Subjects MT and AM possibly detected the difference of the amplitude since the average of the absolute value of the resultant force of inphase pair was 5.2 N and the antiphase pair was 4.8 N. Most subjects specified the force direction by moving their hand. However, we observed no differences between the tandem pairs in how their hand was used when exploring the force direction.



(a) Subject MT

(c) Subject GK

(b) Subject IT

(d) Subject AM

Figure 11: *Scatter pattern of responses as a function of stimuli from three subjects for the inphase tandem pair (open circles) and the inphase tandem pair (filled circles) of the force displays.*

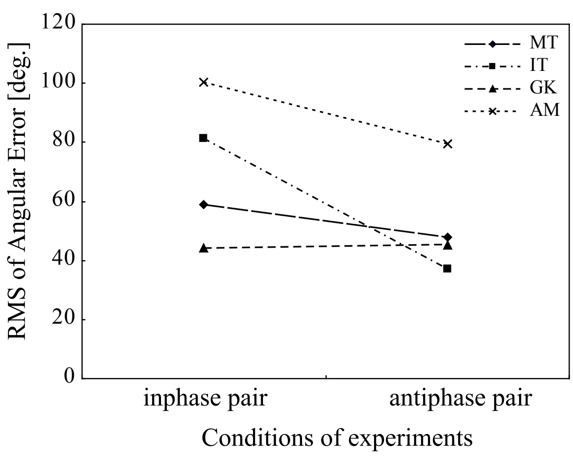


Figure 12: *RMS of angular errors between response and stimuli for each subject.*

5 Experiment: Describe what you feel when holding an antiphase pair of force displays

To confirm the efficacy of the antiphase pair of force displays, we performed an experiment similar to the preliminary experiment: The antiphase pair was held in the air, and we asked naive subjects to describe in words or drawings what they felt as they held it in the air. The subjects were not given any explanation about the principle.

Eight subjects (five right-handed men and three right-handed women, aged 20-39 years old) participated. All subjects were naive to the objectives of the experiment. None had participated in the other experiments reported here.

The apparatus and procedure were identical to the preliminary experiment except that the force display was the antiphase tandem pair, the total reciprocating mass in the force displays was 40 g, and the display was held with the both hands.

Figure 13 shows some examples of the pictures drawn by the subjects. All of the subjects reported a feeling of being pulled, without prompting. The results indicate that the uni-directional force sensation can be more effectively perceived using the antiphase pair.

6 General discussion

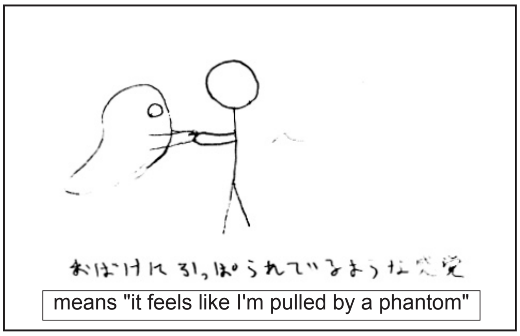
When the two types of tandem pairs of force displays were used, the size of the force vector doubled. With the inphase pair, both the reciprocating force and the swinging force doubled. With the antiphase pair, only the reciprocating force doubled and the swinging force was cancelled. The results of our three experiments indicate the antiphase pair is more effective than the inphase pair in inducing the directed force sensation in the horizontal plane when people held it.

We think the swinging force acts as a masker of the directed force sensation, leading to a simple vibration. This is because the frequency of the swinging force is identical to the asymmetric acceleration and because the differences in the sensations between vibration and directed force result in the existence or nonexistence of the swinging force, as evidenced from the two drawings. This temporal masking would strongly affect the kinesthetic receptors in muscle spindle and tendon, which are the main receptors for perceiving the force vector. Kinesthetic receptors with the directivity in various directions were excited because of the direction change in the resultant force caused by the swinging force. This leads to the ambiguous sensations between vibration and directed force. Our results are consistent with Jones and Hunter's finding that vibration of muscle tendon disturbs the perception of force [11].

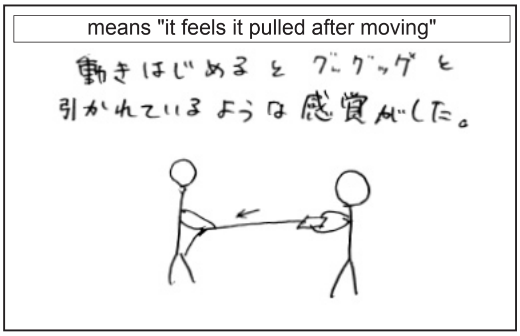
The angular accuracy of the response from two subjects were not significantly different between the two tandem pairs, where data of the reverse-polarity trials were excluded; RMS of the angular errors which excluded over 90 degrees were 24.3° (inphase) versus 25.2° (antiphase) for subject MT (n.s.) and 17.2° versus 18.5° (n.s.) for subject AM. The others were significant; 23.3° versus 15.9° for subject IT ($p<.05$), 24.8° versus 20.9° for subject GK ($p<.05$). We plan to investigate the azimuth accuracy of the perception of the force direction using the static force vector of a grounding force display in order to determine whether the angular errors originated from response resolution of force direction or not.

In our previous research where we fixated a single force display on a linear slider to cancel the swinging force, we thought one of the reasons the proposed display could not get the score of 100 % is that the swinging force is not cancelled perfectly[7][8]. Although the antiphase tandem pair can counteract it perfectly, subjects sometimes perceived the opposite direction of stimuli. The present results indicate that the directions of responses did not perfectly match those of stimuli by only canceling the swinging force. This is because the total mass of the antiphase tandem pair of force displays is considerably large compared with that of the reciprocating objects in the display. Designing a lighter device with a lower power-to-weight ratio (weight/power) than that reported here would be effective for inducing the directed force sensation.

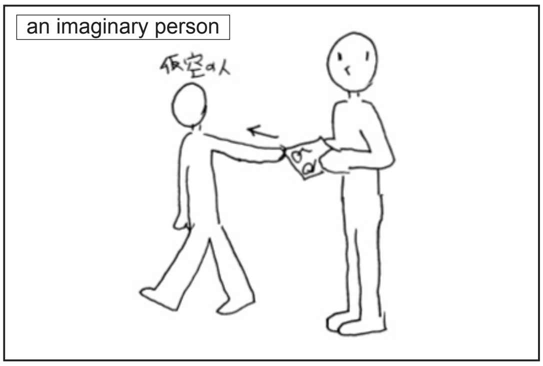
The effect of the swinging force is salient when the reciprocating mass is light. Our results provide a guideline for designers and developers of smaller and lighter device since our nongrounding force perception method is suitable for wearable and mobile use and the force display based on the method must be light. Note that the crank-slider mechanism is not the only way to create asymmetric acceleration. We plan to reduce the size of the force display by using other mechanisms that can produce the reciprocating force without the swinging force.



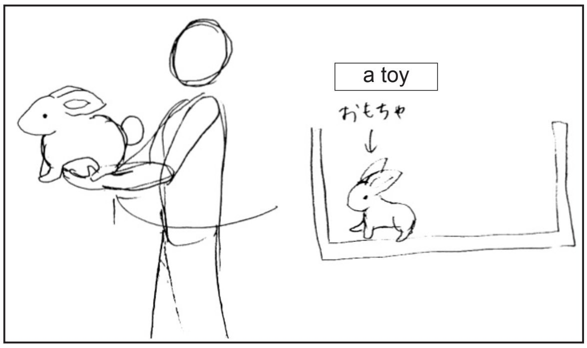
(a) male, right-handed, 21 years of age



(b) female, right-handed, 20 years of age



(c) female, right-handed, 21 years of age



(d) female, right-handed, 21 years of age

Figure 13: *Drawing showing how subjects felt when holding the antiphase tandem pair of the force displays, without explanation about the force display.*

7 Conclusions

We evaluated the characteristics of force perception when the crank-slider mechanism generating asymmetric acceleration was held in the air. Our results indicate that the swinging force generated by the motion of linkages prevents us from well perceiving the force sensation; the motion of linkages makes it difficult for users to distinguish between a simple vibration and the directed force sensation. Moreover, the results revealed that resolution with which the force direction can be discriminated with the antiphase tandem pair is significantly smaller than that with the inphase one. i.e. limiting the direction of asymmetric acceleration to one axis is effective when people hold the force display in the air.

Our results do not merely point to an improvement of the proposed force display, but indicate a criterion to design and develop a force display that utilizes the nonlinearity of perception. We will further investigate the characteristics of the force perception method using more subjects and further develop a guideline for fabricating the force display.

The proposed technology is suitable for applications such as communication, entertainment, and education through the use of mobile devices. In future, all mobile devices will include this technology. Cellular phones that have the device and GPS will intuitively guide you to where you want to go even if you do not watch the screen. We also plan to use this technology to extend the capability of visually impaired people.

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