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RESEARCH ARTICLE

Effect of Rendering Virtual Vibrotactile Motion on the Perceived Lateral Force

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ABSTRACT In the present study, we investigate the effect of rendering virtual vibrotactile motion to the perception of lateral force during planar sweeping motion. The virtual vibrotactile motion was rendered by an algorithm to create the sensation of resistive lateral force utilizing illusory haptic effects. The direction of the virtual vibrotactile motion was the opposite of the hand-sweeping motion to create the sensation of resistive force. We conducted two experiments that mapped the lateral resistive haptic feedback rendered by the virtual vibrotactile motion and force feedback to the perceived force magnitude. In Experiment 1, the test was conducted for three reference stimulus force and two maximum signal intensities. The results indicate significant effect of the two experimental parameters. The perceived lateral force was significantly larger with the virtual vibrotactile motion than the force feedback only. Also, the increase in the maximum signal intensity led to a larger perceived lateral force. Experiment 2 tested the effect of vibrotactile signal envelope function on the perceived lateral force by conducting a comparative experiment for linear and logarithmic envelope functions. The experimental results indicate a significantly larger perceived lateral force for the logarithmic signal envelope function than the linear signal envelope function. Overall, this study suggests that rendering virtual vibrotactile motion at the fingertip during swiping motion can create the sensation of additive lateral force and that the perceived intensity can be controlled by modulating the vibrotactile signal intensity and the signal envelope functions.

INDEX TERMS Haptic feedback, phantom sensation, apparent tactile motion, perceived force, haptic rendering.

I. INTRODUCTION

Most current smart devices work effectively with the aid of touchscreen-based user interfaces, where swiping is one of the most commonly used gestures. A user inputs authentication patterns and scrolls over documents with the swiping gesture. To maximize the user experience, the swipe or lateral finger motion, the haptic feedback has been actively developed from an early stage of the academic field. Researchers proposed various forms of haptic icons that modulate the vibrotactile signal for different icons that the user is swiping over [1], [2]. More complex haptic signals can be generated by utilizing illusory haptic effects such as the apparent tactile motion [3] or the phantom sensation [4]. For example, a 2.5D haptic feedback rendered by a wearable vibrotactile interface could generate the feeling of swiping over a bumpy shape on a touchscreen. However, the effect of applying such illusory vibrotactile actuator for the lateral motion has not yet been quantitatively evaluated, especially in terms of force rendering.

The apparent tactile motion is an illusory tactile effect where a user feels the continuous motion of a single actuator

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moving between closely located vibrotactile actuators [3]. A notable haptic rendering algorithm that used the apparent tactile motion was the Tactile brush proposed by Israr and Poupyrev [5]. The haptic rendering algorithm could create the sensation of a vibrating actuator moving on a 2-D trajectory with sparsely allocated vibrotactile actuators, combined with another tactile phenomenon, phantom sensation [6]. The phantom sensation is another illusory phenomenon in which a user feels a virtual vibrotactile actuator between the two closely located physical actuators. Meanwhile, Zhao et al. applied the apparent tactile motion for a mobile application, where a user could feel the 3D motion of a virtual vibrotactile actuator moving around a tablet [7]. All of the studies above, however, have limitations in terms of quantitative evaluation of human perception, especially in the context of force or kinesthetic feedback rendering.

A wearable haptic interface is a type of haptic feedback display that can usually render force to a user's hand. The wearable haptic interface is typically in the form of a glove. Whenever a user's avatar touches a virtual object, tactile feedback is provided to the fingertips, and the intensity is calculated based on the haptic rendering algorithm. Many of the haptic gloves provide tactile information with force feedback [8], [9]. That type of haptic interface has the advantage of rendering a more vivid tactile sensation by applying force imparted to the joints and tendons in the fingers. However, it is supposed to have heavy actuators, which degrades the interface's usability. Another type of haptic interface is the cutaneous or fingertip haptic interface that stimulates the skin area only at the fingertip for haptic rendering [10], [11]. The cutaneous interface typically has the advantage over the force feedback interface in terms of weight and compact design. Moreover, Kim et al. proposed a fingertip haptic display for a 2.5D haptic system that could render a virtual object's bumpy shape by utilizing the apparent tactile motion and phantom sensation [12]. Compared to the previous fingertip haptic interfaces, it had the advantage of a less complex design and an easy-to-implement algorithm structure. However, the effect of using a virtual vibrotactile actuator for haptic rendering was not fully evaluated in terms of force magnitude.

The multi-modal sensory integration model gives a clue about how virtual vibrotactile actuator rendering affects the perception of force. According to the previous study, when sensory cues with different modalities are integrated optimally, the intensity of the perceived sensation can be increased. For example, the studies on visual-haptic combination indicate that the addition of different modalities increased the perceived intensities of a stimulus [13], [14], [15]. Also, integrating the sensory cues in different modalities shows significant effects on the interaction with the environments in different domains, including virtual reality (VR), augmented reality (AR), and gaming [16], [17], [18], [19], [20]. The same goes for the intra-haptic integration, resulting in the modulation of the perceived friction [21] or surface stiffness [22]. More interesting observations about the intra-haptic integration were found in studies where illusory tactile feedback was applied to the hand. The study of Collins et al. showed the skin stretch on the foreskin of the hand induced an illusory perception of hand posture [23]. Moreover, Bianchi et al. found that the cutaneous feedback at the fingertip can induce an illusory path perception [24]. Both of the previous studies indicate that both kinesthetic and cutaneous information affect the perception of kinesthesia. However, it is not yet clear how rendering a virtual vibrotactile actuator for contact integrates with the kinesthesia.

In the present study, we evaluate the effect of rendering virtual vibrotactile motion on the perception of lateral force at the fingertip as a finger sweeps over a planar surface. Previous studies on multi-modal sensory integration indicate that if inhomogeneous stimuli are optimally integrated, the perceived intensity can be increased. Then, if a virtual tactile stimulus is generated to create the sensation of force along with the gesture, a user may feel resistive force. The fricative force at the fingertip during sweeping motion on a touchscreen is in counter direction of the motion. We, therefore, hypothesize that the perceived lateral force can be increased as the virtual vibrotactile motion is applied at the fingertip, in the opposite direction of the fingertip motion, like a fricative lateral force. Then, if the idea holds to be true, changing the intensity of the virtual vibrotactile motion will result in the variation of the perceived force. To test the idea, we conducted a psychophysical experiment that maps the perceived lateral force rendered both with force and virtual haptic motion rendering by using the apparent tactile motion and the phantom sensation. At the same time, we test the effect of parameters to create the illusory tactile motion of virtual actuator on the perceived force intensities.

The rest of this paper is organized as follows. First, we describe the wearable fingertip haptic interface and haptic rendering algorithm to create the sensation of lateral force as a user sweeps his finger over a virtual plane. In the next section, we elaborate on the experimental procedure for two experiments: i) the evaluation of virtual lateral force matched to perceived force feedback and ii) the comparison of haptic signal envelope functions' effects on the perceived lateral force. Then, we present the experimental results and discuss their implications.

II. GENERAL METHODS

A. HAPTIC INTERFACE

Figure 1(a) shows the CAD image of the wearable fingertip haptic interface housing used for the experiment. The haptic interface is to be worn on the index and the middle fingers of a user's major hand, and two of them were fabricated with a 3D printer for the right and left hands. Inside the left and right end of the interface are installed two dynamic vibration motors (DVM1034, Motorbank Co., Korea) whose resonance frequency is 233 Hz. The housing can be rotated in yaw orientation, connected to a PHANToM Premium 1.0 force

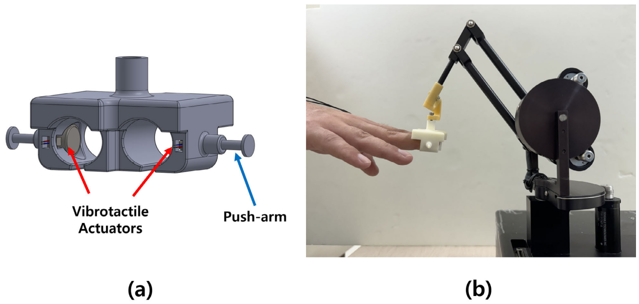

FIGURE 1. Fingertip haptic interface setup. (a) CAD image for the fingertip haptic interface with vibrotactile actuators. (b) Experimental haptic interface with the fingertip interface installed on a force feedback interface, PHANToM premium 1.0.

feedback interface (3DSystems Inc., SC, USA) by a bearing. (Fig. 1(b)). The force feedback interface creates the positional constraint in the normal direction to let a user make a planar motion as s/he is swiping fingers on a touch screen.

B. HAPTIC RENDERING

1) FORCE FEEDBACK FOR HORIZONTAL POSITION CONSTRAINT

We used two illusory effects, apparent tactile motion and phantom sensation, to render virtual vibrotactile motion in the opposite direction of the lateral sweep. The position of index and middle fingertips is tracked by the force feedback interface which has the nominal positional resolution of 0.03 mm. A user can move the fingertips laterally being confined on a virtual plane, whose normal contact force F_n is implemented with a virtual proxy model as follows:

$$F_n = K\left(\boldsymbol{x}_p - \boldsymbol{x}_f\right), \tag{1}$$

where $\boldsymbol{x}_p$ and $\boldsymbol{x}_f$ mean the virtual finger proxy and the physical fingertip position, respectively [25]. For the experiment, lateral force F_{lat} is rendered for a fixed range from the center in the opposite direction of the finger movement as follows:

$$F_{lat}(x) = F_{mag}\left(u(x) - u(x - d_{max})\right), \tag{2}$$

where F_{mag} and d_{max} indicate the lateral force magnitude and the maximum displacement from the center for haptic rendering. For the stability of the force feedback interface, d_{max} was decided as 1 cm.

2) RENDERING VIRTUAL VIBROTACTILE MOTION USING ILLUSORY HAPTIC EFFECTS

Figure 2. shows how the virtual vibrotactile motion is rendered. It is rendered in the opposite direction of the hand motion along with the force feedback to create the sensation of resistive lateral force. As a user's fingertip enters the center of the workspace, the tactile feedback is applied until the distance from the center is 1 cm. For the rendering of the virtual vibrotactile motion to be felt continuously, apparent tactile motion needs to be elicited. A criterion to create

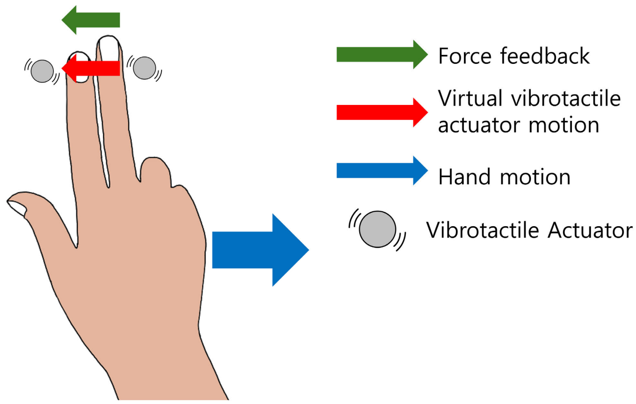

FIGURE 2. Haptic rendering direction. As a user moves the hand (blue arrow), the virtual vibrotactile actuator motion (red arrow) and the force feedback (green arrow) are rendered in the opposite direction, creating the sensation of resistive force.

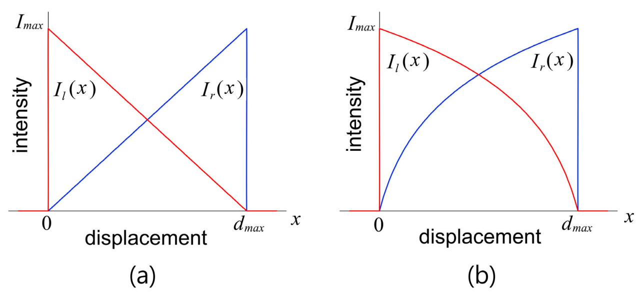

FIGURE 3. Two signal envelope functions for virtual vibrotactile motion rendering. (a) Linear signal envelope function. (b) Logarithmic signal envelope function.

the effect derived from Israr and Poupyrev's experimental observation is as follows [5]:

$$SOA = 0.32 \cdot T_s + 0.0473, \tag{3}$$

where SOA (Signal Onset Asynchrony) and T_s are the time interval between the onsets of subsequent vibrotactile signal actuation and the signal duration, respectively.

The intensity of the vibratory signal is rendered for two envelope functions: i) a linear function, and ii) a logarithmic function, whose basic structure are suggested in the previous [4], [6]. The virtual contact position by the phantom sensation is modulated to move in the opposite direction of the fingertip motion, emulating the fingertip skin being compressed in the opposite direction of the motion due to lateral friction. When the fingertip moves from the left to the right, the vibrotactile signal intensity functions of left $I_l(x)$ and right $I_r(x)$ for the linear intensity rendering by the position x are:

$$\begin{aligned} I_l(x) &= I_{max}\frac{x}{d_{max}}\left(u(x) - u(x - d_{max})\right) \\ I_r(x) &= I_{max}\left(1 - \frac{x}{d_{max}}\right)\left(u(x) - u(x - d_{max})\right), \end{aligned} \tag{4}$$

where I_{max}, and d_{max} indicate the maximum vibrotactile signal intensity and the maximum displacement from the center for haptic rendering, respectively. When the fingertip moves from the right to the left, the vibrotactile signals are rendered in the opposite direction (Fig. 3(a)). For the logarithmic intensity rendering, if the fingertip moves from the left to the right, the vibrotactile signal intensity functions of left $I_l(x)$ and right $I_r(x)$ by the position x are:

$$I_l(x) = I_{max}\frac{\log(x+1)}{\log(d_{max}+1)}(u(x) - u(x - d_{max}))$$
$$I_r(x) = I_{max}\frac{\log(d_{max}-x+1)}{\log(d_{max}+1)}(u(x) - u(x - d_{max})). \tag{5}$$

As is for the linear intensity rendering, when the fingertip moves from the right to the left, the vibrotactile signals are rendered in the opposite direction (Fig. 3(b)).

To elicit the phantom sensation by satisfying the Eq. 3, the SOA needs to be longer than the signal duration as found in [26]. Then, the signal duration should be shorter than 69.8 milliseconds (*ms*), Considering this, the functions of Eqs. 4 and 5 are updated at a rate of 100 Hz.

C. EXPERIMENTAL PROCEDURE

For the evaluation of virtual vibrotactile motion on the perceived force, we adopted the transformed one-up one-down adaptive procedure [27]. The purpose of the experiments in this paper is to estimate how the perceived force rendered with the virtual vibrotactile motion (VVM) with or without force feedback (F_{ref}) is mapped to the perception of the force rendered with force feedback. The one-up one-down adaptive procedure can estimate the point of subject equality (PSE), which can serve as a measure of the perceived force magnitude in N, mapped from the rendered haptic stimulus in VVM + F_{ref} conditions. The experimental procedure lets a participant compare two stimuli in different haptic modalities (VVM + F_{ref} to F) on each trial.

Before the main experiment, a participant was seated in front of an experimental computer and asked to wear a pair of noise-canceling headphones (Beats Solo Pro, Apple Inc., U.S.A). Then, the participant was instructed to insert the index and middle fingers of the major hand to the wearable fingertip interface. A training session was provided before the main experiment to let the participant get accustomed to the stimuli. S/he could feel the haptic stimulus rendered with the virtual vibrotactile motion and force feedback. When the participant felt that s/he was ready, the training session was terminated by the experimenter.

In the main experiment, a participant could see the motion of the fingertip on the screen. Once the experiment begins, white noise is played in the headphones to block possible audio cues from the haptic interface. At the beginning of each trial, a red square moved either from the left or from the right to the opposite position at a speed of 200 mm/sec. Below the red rectangle was located a yellow square which indicated the fingertip position. The participant was instructed to move the fingertip following the red rectangle to ensure a constant lateral fingertip velocity. The reference stimulus for each trial was rendered with the virtual vibrotactile motion and the comparison stimulus rendered with the force feedback only. The reference and the comparison stimuli were presented in a random order.

At the end of each trial, the participant judged which stimulus was felt stronger in terms of the lateral by typing 1 or 2 (1: the first stimulus felt stronger; 2: the second stimulus felt stronger). If the participant felt the comparison stimulus stronger than the reference stimulus, the force magnitude of the comparison stimulus in the next trial decreased by following the one-up one-down adaptive procedure paradigm. Otherwise, the force magnitude of the comparison stimulus increased. In either case, the vibrotactile stimulus did not change.After three reversals of the answer, the step size of the comparison changed to a smaller value to achieve a higher precision in the PSE estimate. After twelve reversals of the answers at the small step size, the experiment was terminated. The experimental program recorded the force magnitude of the comparison objects and the participant's answer.

The experimenter decided whether to repeat another experimental run in case that the result failed to converge. Between two experimental runs, the participant was asked to take a 3-min break to minimize the fatigue in the sense of touch due to the extended exposure to the haptic feedback. The experimental protocol was approved by the IRB at Hongik University, Korea.

D. DATA ANALYSIS

The PSE for a reference tactile stimuli was estimated from the averages of the peak and the valley value when the step size was decreased, which is typical in a transformed one-up one-down adaptive procedure [27]. The PSE estimate values were analyzed for different experimental conditions by conducting repeated measure ANOVAs and t-tests. An α value of 0.05, i.e., 95% confidence level, was used for all statistical analyses in the present study.

III. EXPERIMENTS

The purpose of this study is to evaluate the effect of rendering virtual vibrotactile motion in the opposite direction of motion to the perception of the lateral force. The two experiments in this section are conducted for the purpose and the effect of two parameters deciding the virtual vibrotactile motion are investigated.

A. EXPERIMENT 1: EVALUATION OF RENDERING VIRTUAL VIBROTACTILE MOTION IN LATERAL FORCE PERCEPTION FOR VARIED REFERENCE FORCE

The goal of Experiment 1 is to evaluate the effect of rendering virtual vibrotactile motion to the lateral force perception while changing the reference force. This experiment can see whether the virtual vibrotactile motion itself can be optimally integrated into force by evaluating the effect of vibrotactile stimulus intensity on the perceived lateral force. Previous studies indicated that human perception of vibrotactile intensity can be controlled by the amplitude of the vibratory signal [28], [29]. From the observation, we expected the vibrotactile signal intensity could affect the perceived lateral force of the tactile stimuli rendered with the virtual vibrotactile motion when integrated optimally.

1) METHODS

Sixteen healthy participants (five females, 20 to 26 years old) took part in the experiment. We obtained informed consent from all the participants. None of the participants had any known problem with their sense of touch and were right-handed by self-report.

The experiment consisted of six sessions by three reference force values F_{ref} (0, 1, and 2 N) × two maximum vibrotactile signal intensities I_{max} (0.655 G and 1.31 G, 1 G = 9.8 m/s^2) for the reference stimulus. The larger signal intensity value 1.31 G is the nominal maximum controllable value of the actuator used for the experiment, and the smaller one is half of the larger intensity value. The reference stimulus force values were decided considering the stable force range of the force feedback interface used for the experiment. The duration was decided to be smaller than the 69.8 ms. The comparison stimulus was rendered only with the force feedback. The experiment was conducted by the transformed one-up one-down adaptive procedure. The initial force magnitude of the comparison stimulus was 6 N and the step size for the increase/decrease of the force for the next trial was 0.4 N. After nine reversals of the answers, the step size was decreased to 0.1 N.

Each participant took an average of 1 hour and 20 minutes to complete Experiment 1.

2) RESULTS

Figure 4 shows the result of Experiment 1. When we conducted a two-way repeated measure ANOVA with the factors the reference stimulus force and the maximum vibrotactile signal intensity, the effect of the two factors was found to be significant [F(2,30) = 60.67, p<0.0001, η_p^2 = 0.8 for the reference stimulus force; F(1, 15) = 10.2, p = 0.006, η_p^2 = 0.41 for the maximum vibrotactile signal intensity]. In subsequent Bonferroni analyses, the PSE estimates were not grouped together either for the reference stimulus force or for the maximum signal intensity. When the PSE estimates were compared to the reference stimulus force, significant differences were found for all cases. Additionally, we conducted paired t-tests for the PSE estimates between two maximum signal intensity values. The result indicates a significant difference in the PSE estimates of the two maximum signal intensity values for all the reference force values [t(15) = 0.006, d= 0.65 for F_{ref} = 0 N; t(15) = 0.011, d = 0.74 for F_{ref} = 1 N; t(15) = 0.015, d = 0.55 for F_{ref} = 2 N]. This indicates a significant increase in the PSE estimates by the increase of the reference stimulus force and the maximum vibrotactile signal intensity. The experimental result also indicats that the mean PSE estimates are significantly larger than the reference force for all cases. Overall, the results indicate that rendering virtual vibrotactile motion for the reference stimuli in the opposite direction of fingertip motion led the participants to feel the additive lateral force. Also, the increase in the maximum vibrotactile signal intensity resulted in an increase in the perceived force, as shown by the results of the paired t-tests.

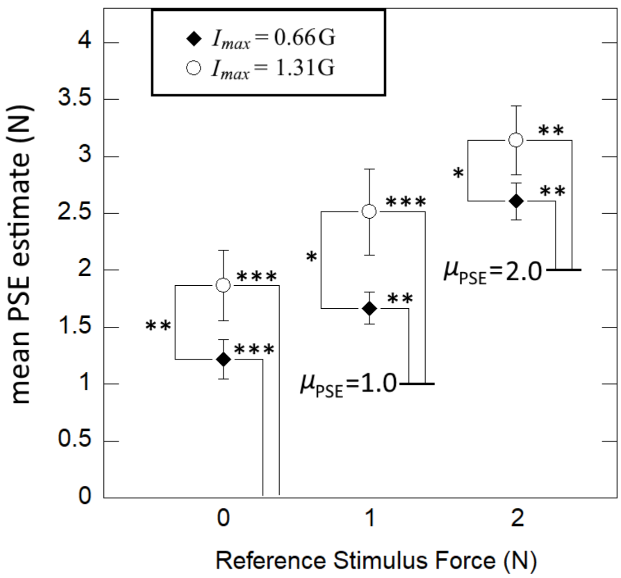

FIGURE 4. Mean PSE estimate of perceived lateral force by reference force and at two maximum vibrotactile signal intensities, I_{max} = 0.66 and 1.31 G. Error bars indicate standard errors (*: $p \le 0.05$, **: $p \le 0.01$, ***: $p \le 0.001$).

B. EXPERIMENT 2: EVALUATION OF RENDERING VIRTUAL VIBROTACTILE MOTION IN LATERAL FORCE PERCEPTION BY SIGNAL ENVELOPE FUNCTIONS

The goal of Experiment 2 is to evaluate the effect of vibrotactile signal envelope functions on the perceived lateral force perception. A previous study on the phantom tactile sensation for a mobile application indicates a significant effect of the vibrotactile signal envelope function on the perceived intensities of the stimuli [6]. Then, the vibrotactile signal envelope function is expected to affect the perceived lateral force, considering the additive nature of the vibrotactile virtual vibrotactile motion from Experiment 1.

1) METHODS

The same participants in Experiment 1 took part in the experiment, which was decided to compare the results of the two experiments that differed in the signal envelope functions.

The experiment was conducted only for the logarithmic signal envelope function in Eq. 5. The experiment consisted of four sessions by two reference force values F_{ref} (0, and 2 N × two maximum vibrotactile intensities I_{max}

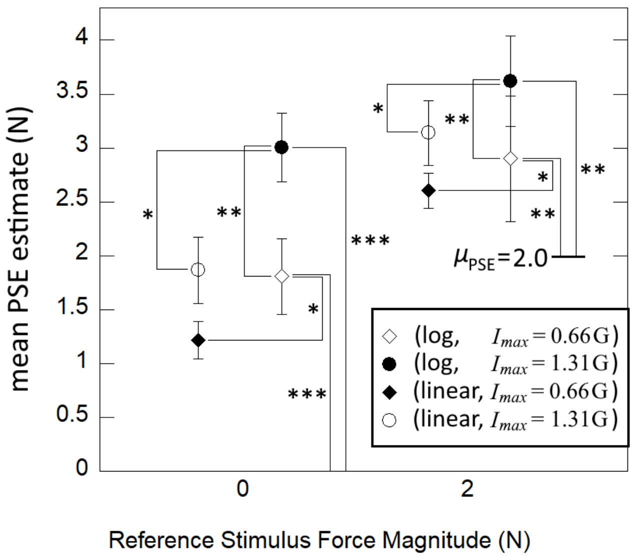

FIGURE 5. Mean PSE estimate of perceived lateral force plotted by two reference force values, two vibrotactile signal envelope functions at two maximum vibrotactile signal intensities, I_{max} = 0.66 and 1.31 G. Error bars indicate standard errors (*: $p \leq 0.05$, **: $p \leq 0.01$, ***: $p \leq 0.001$).

(0.655 G and 1.31 G, 1 G = 9.8 m/s^2) for the reference stimulus. The overall experimental procedure followed that of Experiment 1.

It took about 50 minutes on average for each participant to complete Experiment 2.

2) RESULTS

Figure 5 shows the result of Experiment 2 ((log, I_{max} = 0.66 G) and (log, I_{max} = 1.31G))along with that of Experiment 1 ((linear, I_{max} = 0.66 G) and (linear, I_{max} = 1.31G)). A three-way repeated-measure ANOVA was conducted on the mean PSE estimates with three factors, the reference stimulus force, maximum vibrotactile signal intensity, and the signal envelope function. The results indicate a significant effect of the signal envelop function on the perceived lateral force [F(1,15) = 6.25, p = 0.025, η_p^2 = 0.29]. Meanwhile, a significant interaction was found between the reference stimulus force and maximum vibrotactile signal intensity [F(1,15) = 5.57, p = 0.032, η_p^2 = 0.27]. The significant interaction between the two factors is due to the decreased of the difference in the mean PSE estimates between I_{max} = 0.66 G and I_{max} = 1.31 G as the reference stimulus force magnitude increased from 0 to 2 N, as can be seen in Fig. 5. When paired t-tests for the PSE estimates between two maximum signal intensities were conducted, the difference was significant for the two reference stimulus force magnitudes [t(15)= 0.005, d = 0.56 for F_{ref} = 0 N; t(15)= 0.001, d = 0.42 for F_{ref} = 2 N]. When one-sample t-tests are conducted, the mean PSE estimates are significantly larger than the reference stimulus force values. Overall, the perceived lateral force was significantly larger than the force feedback alone when virtual vibrotactile motion for the reference stimuli was rendered by logarithmic envelope function. When compared to the linear signal envelope function in Experiment 1, the perceived lateral force is significantly higher for all (F_{ref}, I_{max}) pairs.

C. DISCUSSIONS

As demonstrated in the previous sections, Experiments 1 and 2 show that rendering virtual vibrotactile motion in the opposite direction of hand motion can modulate the perceived lateral force. When the haptic feedback was rendered with virtual vibrotactile motion and the lateral reference force (F_{ref}), the PSE estimates were larger than those of the F_{ref} for all experimental conditions. Moreover, the increase of the maximum vibrotactile signal intensities for the virtual vibrotactile motion I_{max} resulted in the increase of the PSE estimates for all the experimental conditions. The result of Experiment 2 indicates the modulation of the vibrotactile signal's envelope function resulted in the significant difference in the perceived lateral force.

A constant and notable trend of the experimental results is that the perceived lateral force as the PSE estimate was larger than the reference lateral force F_{ref} for all the experimental conditions. The experimental results can be partly explained with the optimal integration of multi-modal sensory cues as explained in the previous [14], [30]. Following the model, the perception of lateral force at the fingertip $\hat{S}_{lateralforce}$ can be estimated with the following model:

$$\hat{S}_{lateralforce} = w_K \hat{S}_K + w_C \hat{S}_C, \tag{6}$$

where $\hat{S}_K$ and $\hat{S}_C$ are the estimated lateral force from the kinesthetic and cutaneous cues, and w_K and w_C are their relative weights, respectively. Previous studies indicated that the addition of cutaneous feedback deforming fingerpad synchronized to the force feedback can increase the perceived intensity of tactile cues [11], [22], [31]. As observed from the experimental results, the addition of virtual vibrotactile actuator motion to the force feedback felt from kinesthetic sensation resulted in the increase of the perceived lateral force, as in the case of Eq. 6. Therefore, by comparing the optimal sensory integration model to the experimental result, the virtual vibrotactile motion is expected to have integrated to the perception of the lateral force like the deformation of finger pad, proving our hypothesis.

Another feature of the experimental result is the increase of the perceived lateral force with the increase of the maximum vibrotactile signal intensity. This can be seen as another proof of the multi-modal sensory integration of the virtual vibrotactile motion to the perception of the lateral force. When we see Eq. 6, the increase of $\hat{S}_C$ is to result in the larger $\hat{S}_{lateralforce}$ coinciding with the experimental results. Another explanation can be found in a study that investigated the relation between vibrotactile signal intensity and its neural coding in somatosensory and motor cortex areas. Park et al. investigated the neural coding of vibrotactile signals at three different intensity levels and found a significant correlation between the signal intensity and the neural coding [32].

Applying the findings to the present study, the modulation of the vibrotactile signal intensity would have resulted in the variation of signals, which led the participants to feel the difference in the intensities.

The result of Experiment 2 indicated a significant effect of applying different envelope functions for the vibrotactile signal on the perceived lateral force. A possible answer can be found from the perception of signal in other modalities. Stevens and Hall found that the intensities of loudness and brightness were perceived as the integral of the signals for signal duration period [33]. For haptic perception, a previous study investigating the perceived intensity of vibrotactile signals demonstrated a significant effect of signal duration on the perceived signal intensity [34]. When the Eqs. 4 and 5 are compared, the intensities at the boundaries are identical. Meanwhile, since the logarithm function has a concave shape, the intensity of the vibrotactile signal with the logarithmic envelope function is greater than or equal to that with the linear envelope function. Then, the integral of the vibrotactile signal with the logarithmic envelope function would be larger than that with the linear envelope function, leading to a larger perceived signal intensity.

IV. CONCLUSION

The present study investigated the effect of rendering virtual vibrotactile motion on the perception of lateral force as a user sweeps over a planar surface. We conducted two experiments to see how the additional virtual vibrotactile motion affects the perceived lateral force by varying parameters, the maximum signal intensity, and the signal envelope function. The experimental results show a significant increase in the perceived lateral force with the addition of virtual vibrotactile motion and significant effects of the maximum signal intensity and the signal envelope function. The main contribution of our study is in proposing and validating a method that can render the lateral resistive force using readily available vibrotactile actuators. There are previous studies that attempted to replace the force feedback with cutaneous feedback by using techniques such as sensory substitution, but the efforts to utilize the vibrotactile feedback for the force feedback were limited [35]. Another contribution of this study is providing a quantitative reference on the vibrotactile signal mapped to force feedback. The findings from this study can be utilized to control vibrotactile signals for rendering resistive lateral force.

The findings of the present study can support the research ideas or applications in different research domains. In terms of human perception, the results of the present study can be used as another basis to support the idea of sensory integration, as found in the previous studies. Specifically, the illusory tactile effects creating virtual vibrotactile motion, rarely used for force rendering, are found to substitute the force feedback, as is for the case of cutaneous feedback. Also, the findings of the present study can be utilized to design a more effective haptic feedback interface for VR and AR applications. For example, the experiment results showed that virtual vibrotactile motion rendered only with vibrotactile feedback could lead the participants to feel the lateral force feedback. It implies a possible application of the virtual vibrotactile motion for a lightweight tactile interface, not with force feedback, typically requiring heavy actuators and links.

Our future work will further investigate the effect of applying virtual vibrotactile motion on haptic perception. In the present study, we constrained the direction of the vibrotactile motion in the opposite direction of hand motion to mimic the fricative resistive force. Considering the limitation, we plan to test whether the direction of the virtual vibrotactile motion affects the perceived intensity of lateral force. Another limitation of the present study can be found in the lack of an analysis of how a participant's characteristics may affect the experimental results. For example, we could not analyze the effect of handedness on the experimental results because all the participants were right-handed. Thus, in future work, the effect of the participant's age, gender, and handedness on the perception of virtual vibrotactile motion will be further analyzed with sufficient subjects. We are also planning to conduct a study on the perceived force comparing cutaneous feedback and virtual vibrotactile motion to create the effect of lateral resistive force.

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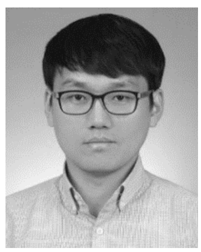

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