Directional Vibration Sensitivity of Finger for Haptic Feedback Switch Design

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I. INTRODUCTION

The adoption of vibration-based haptic switches in automobiles is steadily increasing, driven by their potential to enhance safety by minimizing the required duration of visual attention. In a study aimed at achieving a high-quality operational feel in automotive haptic switches, findings suggested that the direction of vibration may significantly impact sensory evaluation results [1].

This study aims to investigate the directional sensitivity of vibratory perception at the fingertip, identify the most perceptible vibration orientation, and establish concrete design guidelines for switch components to optimize the effectiveness of haptic feedback.

II. HAPTIC SWITCH

The tactile experience of a switch is governed by the mechanical stimuli conveyed to the user's fingertip, as well as the auditory cues produced during actuation. In pressure-sensitive haptic switches, the tactile sensations that typically arise from the displacement of an internal spring in mechanical switches are emulated through controlled vibratory feedback, eliminating the need for physical springs or moving components. A distinctive characteristic of these haptic switches is the absence of actual displacement; instead, time-synchronized vibration patterns are employed to replicate the buckling behavior of a mechanical spring, thereby conveying a realistic sensation of actuation.

III. EXPERIMENTAL ENVIRONMENT

Hwang et al. [2] conducted experiments where vibrations were applied in different directions to the fingertip by rotating the orientation of a mini-shaker that vibrated along a single axis. The mini-shaker was mounted onto a cubic enclosure composed of an aluminum frame and acrylic panels, and directional changes were achieved by rotating this enclosure. This study replicated the system architecture to construct an equivalent experimental environment.

Fig. 1 presents an overview of the experimental setup. The mini-shaker fixed to the experimental apparatus receives frequency and amplitude signals from the function generator and generates vibrations accordingly. A triaxial accelerometer mounted on a mini-shaker sends vibration data through a signal conditioner to a PC via an analog input terminal for analysis. The conditioner amplifies the accelerometer's output, which is then digitized by the terminal for subsequent PC-based logging. A force sensor, also connected to the PC, enables real-time monitoring of applied fingertip pressure.

To apply vibrations along each of the three orthogonal axes to the fingertip (Fig. 2), it was necessary to alter the vibration direction of the mini-shaker, which operates in a single axis. To achieve this, the cubic enclosure containing the mini-shaker was designed to rotate, allowing for changes in the applied vibration direction.

Participants were prevented from seeing the experimental apparatus and were instructed to wear earmuffs to eliminate auditory cues.

IV. VIBRATION STIMULI

Following the methodology of Hwang et al., vibration frequencies of 150Hz and 280Hz were employed in this study. The 150Hz frequency lies within the range where the absolute threshold for vibration perception is considered to be at its lowest [3], thereby maximizing sensitivity. Conversely, 280Hz falls outside this optimal frequency band and may elicit different perceptual responses.

To determine the appropriate stimulus intensities for the main experiment, a pilot study was conducted. Four right-handed male participants aged between 21 and 23 years

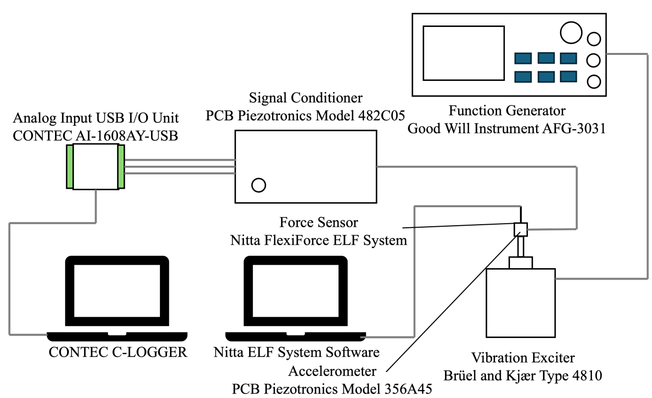

Figure 1. Schematic diagram of experimental setup

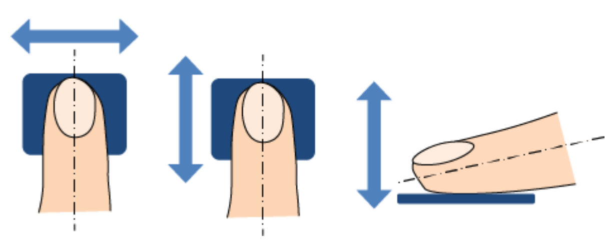

Figure 2. Direction of vibration to fingertip

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took part in the pilot study. The experiment was carried out under six conditions, comprising two frequencies and three vibration directions. Participants used the index finger of their right hand and were given approximately two seconds to perceive each vibratory stimulus. For each condition, participants completed two trials: one in ascending series and one in descending series of stimulus intensity.

For each series, the midpoint between the intensity at which the stimulus was perceived and the intensity at which it was not perceived was recorded and used as the estimated absolute threshold. A total of eight estimated threshold values were obtained for each condition. The mean of the 24 estimated threshold values for each frequency condition was calculated and set as the median stimulus intensity for the main experiment. Three additional stimulus intensities were then set at equal intervals above and below this median, resulting in a total of seven stimulus levels per condition.

V. Vibration Sensitivity Experiment

A. Method

In the study by Yasuda et al. on the operational characteristics of haptic switches, it was shown that the actuation force required to press the switch is 5N [1]. Accordingly, this experiment examined the effect of stimulus direction on vibration sensitivity when the fingertip applies a force of 5N.

The 15 participants were between 21 and 24 years old; 11 were male and 4 were female; 13 were right-handed and 2 were left-handed.

Before the experiment, participants were given a general explanation of the study, including instructions on how to perceive the test stimuli and how to respond to them. The experimental procedures were thoroughly explained, and informed consent was obtained from all participants prior to their involvement.

Each of the seven stimulus levels was presented five times in a randomized order. For each vibratory stimulus, whether the participant perceived it was recorded, and the detection rate was calculated for each intensity level. Following the method of Hwang et al., the collected data were fitted with a psychometric curve, and the vibration intensity corresponding to a detection rate of 0.5 was regarded as the absolute threshold for vibration perception.

B. Results

At a frequency of 150Hz, the absolute thresholds for the right hand exhibited no significant variation across different vibration directions. In contrast, for the left hand, the mean absolute threshold was lowest along the Z-axis. At 280Hz, the right hand also demonstrated the lowest threshold in the Z-axis direction. For the left hand at this frequency, the highest mean threshold was observed along the X-axis, while the lowest remained in the Z-axis direction (Table 1).

To determine whether these differences were statistically significant, an analysis of variance (ANOVA) was conducted (Table 2). The results indicated that frequency had a significant effect, whereas the direction of vibration and handedness did not show statistically significant effects.

TABLE I. Absolute Threshold at 5N (Average ± SD ($\times 10^{-2}$G))

	150Hz		
	X axis	Y axis	Z axis
Right hand	14.6 ± 4.22	14.7 ± 4.12	14.5 ± 3.50
Left hand	14.7 ± 3.50	14.9 ± 3.73	13.6 ± 3.43

	280Hz		
	X axis	Y axis	Z axis
Right hand	19.3 ± 6.13	19.0 ± 6.12	17.9 ± 5.47
Left hand	19.5 ± 5.95	18.7 ± 6.56	17.6 ± 5.80

TABLE II. ANOVA Table for Effects on Absolute Threshold

	df	Type III SS	Mean square	F value	Pr > F
Direction	2	20.15	10.08	0.16	0.851
Frequency	1	2010.60	2010.60	32.29	<0.001
Hand	1	0.17	0.17	0.003	0.959

VI. Conclusion

This study was conducted with the objective of clarifying which vibration direction elicits the highest sensitivity in the fingertip. The experimental results yielded valuable insights that can inform the design of haptic switches. It was found that, under conditions where a relatively large force is applied to the fingertip, such as during switch operation, the direction of vibration does not influence perceptual sensitivity. In other words, the direction of vibration does not significantly affect the user's experience at pushing force 5N.

Although this study found no significant differences in perceptual sensitivity based on vibration direction, previous research [2] has reported directional sensitivity differences when the fingertip applied a force of 0.8 N. This suggests that the amount of force applied by the fingertip may affect vibration sensitivity. In automotive haptic switches designed for use while driving, the typical actuation force is around 5 N. In contrast, some touch panels and other devices respond to much lower input forces. Therefore, the relationship between fingertip force and vibration direction sensitivity warrants further investigation. Furthermore, it is necessary to increase the number of trials per participant to obtain more accurate and reliable estimations. In addition, examining the effects of different vibration waveforms on perceptual sensitivity is essential for the effective design of haptic switches.

References

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