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Perception of Diverse Asymmetric Vibration Signals

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I. Introduction

Asymmetric vibration is a promising method to present directional haptic cues in portable systems: a mass subjected to unequal accelerations in opposing directions can be perceived as applying a lateral pulling sensation on the user's fingertips [1]. However, the psychophysical mechanisms underlying this effect remain unclear, particularly which input signal attributes or motion features influence the strength and direction of the pulling sensation that a person perceives. Additionally, differences in actuator mechanics have made it challenging to replicate findings across devices, requiring different types of input signals (e.g., square, sine, saw-tooth) to generate the pulling effect.

To address this gap in understanding, previous research has proposed metrics designed to represent the strength of the pulling sensation based on aspects of the actuator motion, such as the peak skin displacement in the intended and unintended directions [2] or the difference between the peak jerk in the intended and unintended directions [3]. However, to the best of our knowledge, no consensus exists about which feature or metric best predicts the pulling sensation. Previous research has also not considered how applied grip force could affect perception, despite evidence that varying the normal force experienced by a fingertip changes its lateral mechanical response [4]. A more complete understanding of how signal design, resultant motion, and applied grip force affect perception is crucial for advancing asymmetric vibration guidance systems.

II. User Study and Analysis

We conducted a user study to investigate the impact of input signal parameters and measured grip force as well as the resulting acceleration profile on the perception of the pulling force created by asymmetric actuation signals.

Twenty adults (aged 23–41) took part in the study, which was approved by the Max Planck Ethics Council. Each participant interacted with a custom graphical user interface using their left hand while holding a sensorized linear voice-coil actuator (Haptuator Mark II, Tactile Labs) with their right hand in a pinch grip (Fig. 1A). The actuator was instrumented with a three-axis analog accelerometer (ADXL377) to measure linear acceleration and two ultra-thin capacitive sensors (SingleTact S8-10N) to record grip force. We generated a set of 54 diverse current commands by varying four parameters of the step-ramp vibration signal, as shown in Fig. 1B: direction (left/right), amplitude (0.1, 0.3, 0.5 A), frequency (30, 50, 100 Hz), and dwell time (0, 25, 50%). Three repetitions of the 54 signals were presented in randomized order, resulting in 162 trials per person. After each two-second stimulus, participants rated the combined direction and strength of the perceived pulling sensation of the vibration on a visual analog scale ranging from 0 (left) to 100 (right); a value of 50 corresponded to neither left nor right. After completing the study, participants answered a post-experiment questionnaire consisting of six NASA Task Load Index (NASA-TLX) questions and six open-ended questions about their experience in the study. Due to the setup's unexpected disturbance of leftward stimulus perception, our analysis of this study focuses only on rightward stimuli.

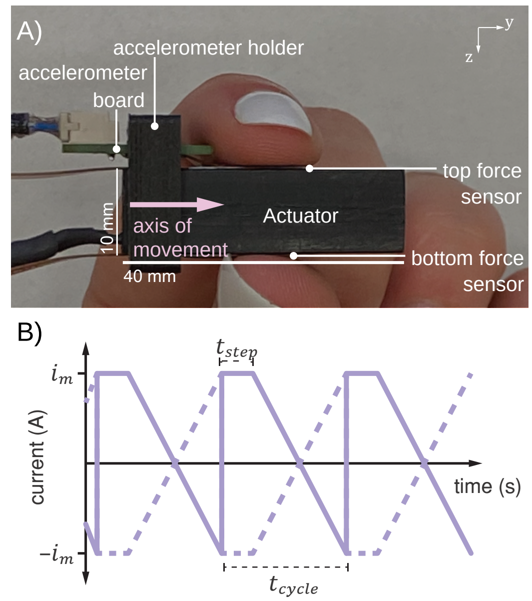

Fig. 1. A) A cross-sectional side view of the instrumented actuator (Haptuator Mark II) held between the index finger and thumb with sensors labeled. B) An example of the step-ramp input signal presented in the study. The solid line represents the right-oriented control signal while the dashed line the left-oriented control signal. Dwell is defined as t_{step}/t_{cycle}, amplitude as i_m, and frequency as $1/t_{cycle}$.

A. Data Analysis

We evaluated the perceived direction of signals, binning each response into three categories: "left" (0–47.5), "right" (52.5–100), and "unsure" (47.5–52.5).

Acceleration along the movement axis of the actuator was

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filtered, averaged across one period, and used to compute six acceleration-based metrics. Two of those metrics were taken from previous work: (1) effectiveAccRatio [5] is the root mean square (RMS) of the acceleration profile in the intended direction divided by the RMS of the acceleration profile in the unintended direction and (2) peakJerkDiff [3] is the difference between the peak jerk (rate of change of acceleration) in the intended and unintended directions. In addition to these existing metrics, we propose four new metrics: (3) peakAccRatio, inspired by Culbertson et al. [2], is the ratio between the peak acceleration values in the intended and unintended directions; (4) peakAccDiff, the difference between the peak acceleration values in the intended and unintended directions; (5) peakAccDiffNorm, which is equivalent to peakAccDiff divided by the value of the peak-to-peak acceleration; and (6) peakAccSum, the sum of all positive and negative peaks in one cycle.

We investigated the effects of these six acceleration-based metrics as well as grip force, index-finger and thumb sizes, and the three parameters of the input signals (amplitude, frequency, and dwell) on the perceived pulling sensation (i.e., perceived magnitude and direction combined), using a beta-distributed generalized linear mixed model (GLMM).

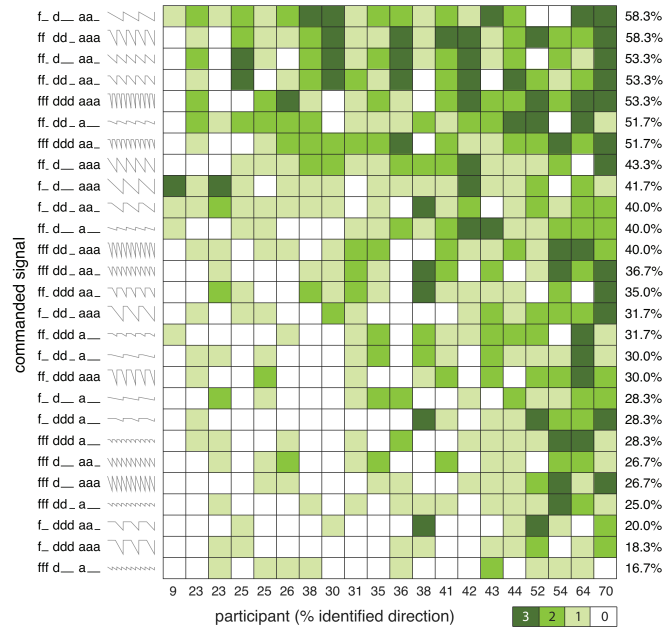

Fig. 2. A heatmap showing the number of correctly identified trials for each participant (x-axis) and input signal (y-axis) for the right-oriented trials. The color of each cell corresponds to the number of times the intended direction of the signal was correctly identified by the participant.

III. Results and Discussion

The direction identification rate for the pulling sensation in the right direction (Fig. 2) varied widely across different control signals. The 30 Hz signal with 0% dwell and 0.3 A amplitude (f__, d__, aa_ in Fig. 2) and the 50 Hz signal with 25% dwell and 0.5 A amplitude (ff_, dd_, aaa) had the highest correct identification rate of 58.3%. Only seven out of 27 control signals were identified at rates above chance level.

Interestingly, direction identification was also highly subject-dependent, with individual accuracy ranging from 9% to 70%. Only four out of twenty participants correctly identified more than half of the trials, though one should keep in mind that the pulling illusion is subtle for many of the tested stimuli. Across all participants, the mean identification rate was 37.0%, with a standard deviation of 15.0%.

These results are in line with the open-ended responses: participants had divergent perceptions and experiences with the same hardware and the same set of stimuli, suggesting large individual differences in perceptual sensitivity and interpretation and/or time-varying delivery of the stimuli in the study, perhaps caused by pulling of the sensor wires.

The results of the statistical analysis indicated that the interaction between amplitude and dwell significantly affected perception ($\beta = -0.64$, $SE = 0.20$, $z = -3.23$, $p = 0.0013$). Among the frequencies tested, signals at 50 Hz had the highest identification rates, while those at 30 Hz and 100 Hz were often misidentified. Of the six acceleration-based metrics, only two metrics, peakAccRatio and peakAccDiffNorm, significantly impact the perceived pulling sensation ($\beta = 2.11$, $SE = 0.81$, $z = 2.59$, $p = 0.0095$ and $\beta = -1.79$, $SE = 0.66$, $z = -2.69$, $p = 0.0072$, respectively). These metrics relate the peak acceleration in the intended direction to that in the unintended direction, suggesting that indeed the peak acceleration values are the only features of the actuator movement needed to predict the resulting pulling sensation.

Designers need rubrics to efficiently select asymmetric vibration signals that will be effective on different devices; given our results, we believe that considering the peak accelerations induced in both directions by applying a given asymmetric vibration signal to the selected actuator may be a good predictor of the pulling sensation it will evoke. These insights on key parameters of asymmetric vibrations help advance the understanding needed to design effective ungrounded directional haptic feedback for applications in virtual reality, remote control, and assistive technologies.

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