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There Is the Force: Signal Asymmetry and Power in Pseudo-Force Perception

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I. Introduction

It is now well known that asymmetric vibrations create a pseudo-force - an illusion perceived as a continuous pulling or pushing sensation. This phenomenon is believed to occur due to nonlinear encoding of the vibrations by mechanoreceptors, so that a purely zero-mean harmonic signal is perceived as a continuous force [1], [2]. Leveraging this illusion for haptic feedback has great potential for future applications as it enables force feedback via lightweight, wearable devices. However, the underlying perceptual mechanism of the waveform is still not well understood, and the design space of waveforms has not been fully explored. From the literature, it is unclear how the key parameter, the level of asymmetry, influences perception. Therefore, it is essential to understand the correlation between the asymmetry and perceived pseudo-forces by human participants. Several researchers studied the induced pseudo-force (pulling sensation) dependency and the waveform parameters, such as frequency and asymmetry rate [2]–[4]. Their findings proved that illusion occurs at 40-75 Hz frequencies and a particular pulse width of the specific control signals.

In this study, we seek to understand how the parameters of the asymmetric waveform affect the salience of the illusion. To do so, we explored how the degree of asymmetry affects the perceived strength of the pseudo-force illusion. We found that the perceived pseudo-force, while the overall vibration intensity remains constant, correlates with an increase in asymmetry of the waveform. To reach these findings, we invited 20 participants to discriminate the strength of the pseudo-forces during a 2-AFC protocol, where we collected the rate of answers and calculated the Just Noticeable Difference (JND) when varying the asymmetry of the signal.

II. Materials and Methods

Twenty participants, 25-35 years old (mean: 28.25, standard deviation (SD): 2.41, 7 women), took part in the study. All participants were right-handed and had not experienced pseudo-forces before. The experiment was approved by the Human Research Ethics Committee of TU Delft.

In this work, we define asymmetric waveform vibrations as waveforms with different durations of the positive and negative parts of the signal (asymmetry within the time axis) and different positive and negative peaks within one period (asymmetry along the amplitude direction). The asymmetry ratio is defined as a ratio between the positive (t_P) and negative (t_N) durations of the waveform within a cycle. When the asymmetry ratio equals one, the waveform has a symmetric sinusoidal shape and the illusion is not observed; when the asymmetry ratio decreases, the asymmetry of the signal increases (Fig. 1a). In this experiment, the asymmetry ratio was changed between seven discrete asymmetry values in the range [0.25 – 0.85], based on preliminary experiments. For the designed stimuli, the overall vibration intensity, defined as energy of the signal, with all the ratios remaining constant: $E_P + E_N = const$, for $r \in [0.25\text{–}0.85]$ (Fig. 1b). Based on preliminary studies, the fundamental frequency of the signal was set to 70 Hz and remained constant throughout the experimental procedure. We hypothesize that as the asymmetry of the waveform increases, the intensity of the perceived pulling sensation increases accordingly.

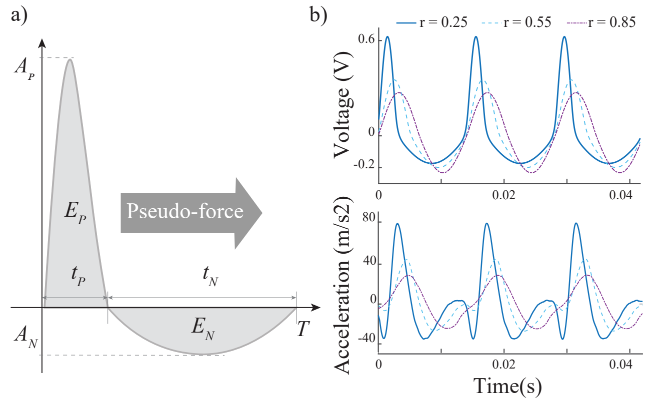

Fig. 1. **a**. Concept for asymmetric control signal design: $r = t_P/t_N$ and $E_P = E_N$, where t_P, t_N - duration, E_P, E_N - energy of positive and negative parts of the signal respectively; **b** Examples of designed control asymmetric signals (upper image) and corresponding output acceleration profiles (lower image) for different asymmetry ratios .

Two-alternative forced choice (2AFC)

The JND of perceived pseudo-forces was estimated using a constant stimuli method. To determine how the asymmetry ratio correlates to the perception of intensity of a pseudo-force, we presented participants with two stimuli sequentially. We asked them to report which was 'pulling stronger' using a two alternative forced choice task (2AFC). According to the chosen procedure of the method of constant-stimulus [5], a 'reference' stimulus was fixed (reference asymmetry ratio $r = 0.55$), and compared with a group of 'comparison' stimuli (different asymmetry ratios). The psychometric function was modeled as a sigmoid curve, P("stronger than

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reference") = $\psi(Ax + B)$, where ψ is a sigmoid curve and x denotes the perceived intensity of the comparison stimuli, which was assumed to be linearly related to the pseudo-force. A pair of reference and randomly selected comparison stimuli was presented to the participants. The comparison stimulus was selected from seven different levels of asymmetry ratio.

Experimental apparatus and procedure

The actuator Actronika Hapcoil-One generated the asymmetric vibrations. The signals were sent from a laptop to a digital-to-analog converter (DAQ NI-2611 USB), then amplified with a linear amplifier (Texas Instruments OPA548). We used the accelerometer (Endevco Model 2250A-10) to measure the output acceleration profile. The analog converter of the DAQ was set to 10 kHz. During the experimental procedure, participants were holding the actuator with two fingers (index and thumb) of their right hand . Participants were wearing noise-canceling headphones (Edifier W830NB). During the experiment, vibrations with different asymmetry ratios were presented to participants in pairs. Each stimulus was presented for 1 second and had a 1-second break in between; pairs were not repeated. There were 140 pairs, divided into four groups by 35 comparison pairs, with a 1-minute break between the groups. Prior to the study, participants were introduced to the asymmetric vibrations and experienced the pulling sensation to the right and the left sides several times (corresponding to the positive and negative asymmetry, respectively). They were asked to identify which direction they felt the pulling towards, and all of the participants identified the presence of pseudo-forces towards the desired directions, as well as a clear understanding of directional change. The familiarization part lasted approximately 30 seconds and included 4-6 reversals; the asymmetry ratio was unchanged. We expected that the perception of pseudo-force depends on the direction of the pulling force. During the experimental stage, both stimuli in a pair provided the pseudo-force in the same direction, with half of the pairs having the right direction and the other half, left. Pairs were presented in a random order to every participant. Each stimulus was accompanied by a visual cue of the direction ("$\rightarrow$" or "$\leftarrow$" on the screen). Participants were seated in front of the screen with instructions displayed during the experiment; the haptuator was hidden from the participant with a view-blocking screen. Participants put in the answer (1 or 2) after each comparison pair with a keyboard and their non-dominant hand.

III. Results and discussion

The results of the study showed that there is a strong correlation between asymmetry and perceived pseudo-force, with the higher asymmetry causing higher perceived pulling force: Spearman correlation $\rho = 0.77$, $p < 0.001$. Participants shared after the study that it was easy to follow the directional cue in all pairs. However, sometimes it was easier to choose the stimulus in a pair in a particular direction. There is no statistically significant difference in perceived pseudo-forces in one or the other direction for different asymmetries (ANOVA: $F(1) = 0.11, p = 0.74, \eta^2 = 0.004$). Even though the duration of vibration stimuli was chosen to minimize fatigue, it was enough to perceive the pseudo-force [3]. The performance and correctness rate remained stable throughout the trials, and there is no observed tendency of fatigue or learning effect (for correctness level to the number of trial Likelihood Ratio Test: p = 0.70). Nevertheless, some participants reported feeling less sensitive and accurate in the discrimination of pseudo-forces by the last group of comparison pairs. For every pair of stimuli, the participant's response indicating the stronger pulling sensation was translated into the number of choices for each of the seven comparison ratios (Fig. 2b). The curve fitted across the median values of all participants $P(\text{"comparison stronger"}) = 1/(1 + e^{(\alpha - x)\beta})$, where $\alpha = 0.55$, $\beta = 4.85$. That gives a JND estimation for the chosen asymmetry parameter: PSE = 0.55, JND = 0.22. This finding provides insight into the perception mechanism of pseudo-forces and evaluates the sensitivity of the pseudo-force to asymmetry in the signal, given the constant energy of the vibrations. In a post-study interview, the participants felt it took longer to decide when the difference was less noticeable. In future studies, we will analyze the response time as a metric to assess the level of confidence in the perceived illusion. We will also investigate the impact of the signal energy and acceleration peaks on the perceived pseudo-forces for different asymmetry ratios to connect the sensation to physical parameters.

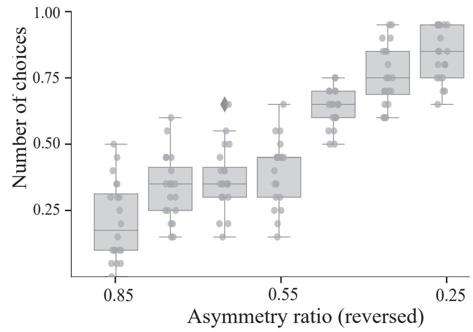

Fig. 2. Normalized ratio of choices for "comparison stronger" for the designed psychophysics experiment.

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