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The illusory sensation of being pulled arises from fingertip skin deformation and its velocity

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I. Introduction

Understanding how our force perception arises from cutaneous sensation is crucial for designing haptic devices and revealing the secrets of dexterous manipulation. To gain insights into the computational basis of directional force perception, the present study focuses on an illusory tactile pulling sensation elicited by asymmetric vibrations and explores its underlying mechanisms.

Although previous studies have investigated how the vibratory waveform relates to this illusion, the key kinematic contributor remains unclear. Tanabe et al. [1] found that peak asymmetry in jerk (i.e., the difference between positive and negative peaks) may be critical, while other studies have reported similar illusions with asymmetry in position [2]. The difficulty in determining the primary factor may be explained by the mixed contribution of proprioceptive cues and skin deformation, as participants in these studies held the vibration device without hand fixation, allowing for subtle hand or finger movements.

To address this issue, we aimed to identify the cutaneous contribution by presenting vibrations to a fixed fingertip. The extracted features included position, velocity, acceleration, and jerk of the skin deformation, as well as the contact force and its time derivative (force velocity) at the skin-device interface. Generalized linear mixed models (GLMMs) were used to analyze the relationship between the peak asymmetry in these features and the participants' perceptual responses.

II. Methods

Fig. 1 shows the experimental setup. Participants (n = 10) had the volar surface of their right index finger fixed in an upward-facing position. The finger was secured to the table using double-sided tape and a participant-specific fingernail mold. Vibration along the transverse axis of the finger (i.e., left to right from the participant's viewpoint) were delivered to the fingertip using a Phantom Premium 1.5 device and participants reported the direction of the perceived pulling force using a keyboard (two-alternative forced-choice). Each stimulus lasted 1.5 seconds, followed by a 5-second inter-trial interval.

Following the previous study [1], the vibratory waveform was constructed by combining two sine waves, as:

$$x(t) = A_1 \cdot \sin(\omega t) + A_2 \cdot \sin(2\omega t + \varphi) \,, \quad (1)$$

where $x(t)$ represents skin deformation, with the positive direction defined as rightward from the participant's viewpoint. The amplitudes A_1 and A_2 were set to 0.4 mm and 0.1 mm, respectively. The angular frequency ω was defined as $2\pi f$, where $f = 40$ Hz. The phase difference φ was varied from 0° to 315° in 45° increments, resulting in eight stimulus conditions. This waveform design enabled systematic control of the peak asymmetry in skin deformation (i.e., position) and its kinematic features: velocity, acceleration, and jerk. Peak asymmetry was calculated as the difference between the positive and negative peaks of the vibratory waveform (Fig. 2). The phase differences that produce the maximum and minimum asymmetries shift by 90° across these four features (Fig. 3). Comparing these shifts with the perceived pulling directions reported by participants allows us to infer which features contribute to the illusion. Each condition was tested in 20 trials in random order (160 trials per participant). The motor signal for driving the device was adjusted for each participant to generate the desired skin deformation.

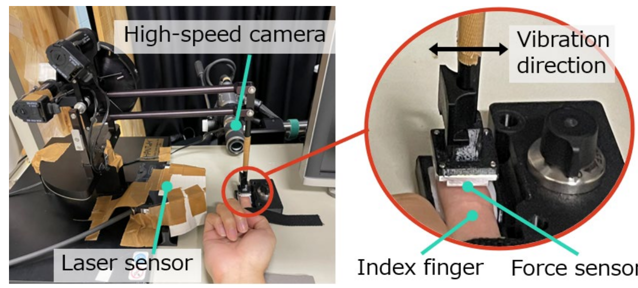

Figure 1. Experimental setup.

The trajectory of the Phantom tip and the contact force at the fingertip were measured using a laser displacement sensor (Keyence, LK-G80) and a force sensor (Tech Gihan, USL06-H5-50N), respectively, both sampled at 10 kHz. A high-speed camera (Keyence, VW-9000) recorded fingertip skin deformation at 1 kHz for validation.

Since participants' responses were binary, GLMMs were constructed assuming a binomial distribution with a logit link function. The models predicted the responses based on combinations of eight fixed effects: peak asymmetries in skin deformation (position, velocity, acceleration, jerk) and in contact force (force, force velocity), and small biases in position and force caused by finger fixation. Participant-specific random slopes accounted for individual variability. Model selection was performed using the AIC. All fixed effects were Z-score standardized prior to the fitting to assess the relative contribution of each effect.

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III. Results

Fig. 3 illustrates the six peak asymmetries calculated from the experimental data. The blue box plots represent the actual asymmetries derived from the measured data, while the red dots indicate the ideal asymmetries. Ideal values were not defined for force and force velocity. The overall trend in the measured biases, averaged across all trials, revealed a slight leftward tendency: the mean position bias was -0.09 mm and the mean force bias was -0.012 N.

Black line in Fig. 4(a) shows the participants' responses plotted against phase difference. The illusory sensation was most frequently perceived as rightward at a phase difference of 270°, and as leftward at 90°. Using GLMMs, the responses were fitted by the features derived from measured data. Model comparisons based on AIC are summarized in Table I. The best-fit GLMM consisted of the peak asymmetries of position and velocity, along with position bias. The model's predictions (blue line, Fig. 4(a)) closely matched the observed responses. As shown in Fig. 4(b), standardized coefficient estimates revealed that position asymmetry had the most pronounced effect, followed by velocity asymmetry. The inclusion of position bias slightly improved model fit (+2.553 AIC),

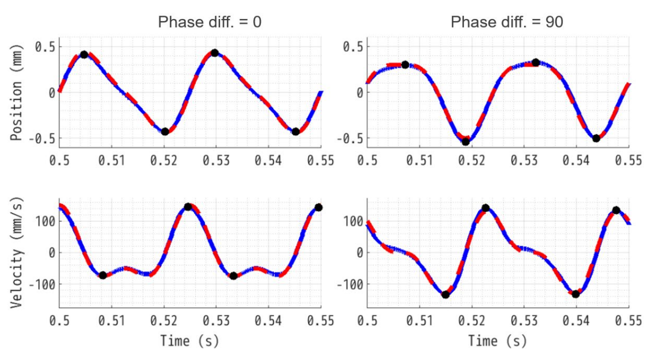

Figure 2. Measured (blue) and ideal (red dashed) waveforms of position and velocity at phase differences of 0° and 90°. Black dots indicate positive and negative peaks used to compute peak asymmetry.

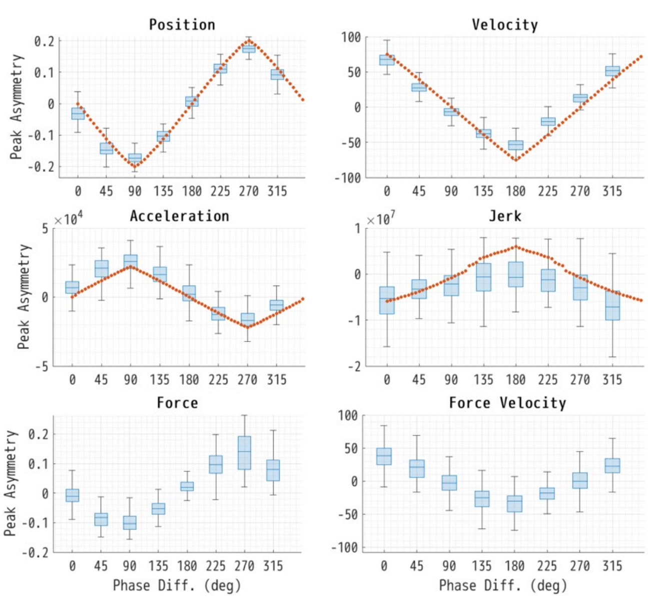

Figure 3. Peak asymmetries of six features vs. phase difference. Units: position (mm), velocity (mm/s), acceleration (mm/s²), jerk (mm/s³), force (N), force velocity (N/s).

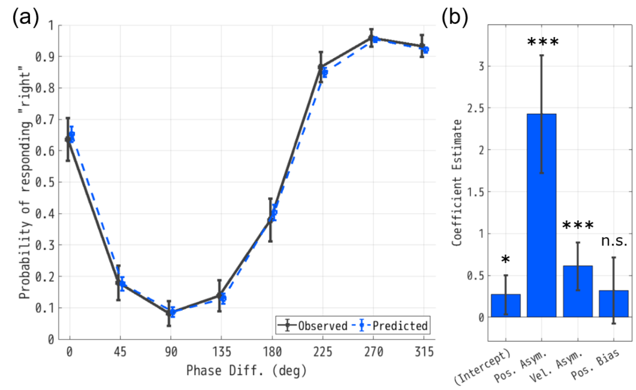

Figure 4. (a) Participant response probabilities (black line) and model predictions (blue dashed line) vs. phase difference. Error bars: 95% CI. (b) Standardized coefficient estimates from the best-fit model. Error bars indicate 95% CI. Asterisks denote statistical significance from zero ($p < 0.05$: *, $p < 0.001$: ***); n.s., not significant.

TABLE I. AIC difference vs. best model

Model	**AIC difference**
Pos. asym. + Vel. asym. + Pos. bias (best)	-
Pos. asym. + Vel. asym.	+2.553
Force asym. + Force vel. asym.	+65.66
Pos. asym. only	+108.8
Force asym. only	+178.7

although its coefficient was not significantly different from zero (p = 0.1089) in the best-fit model. Alternative models incorporating force-related features or fewer predictors showed substantially worse fit, indicating the limited explanatory power of those features.

IV. Conclusion

In this study, we investigated the influence of skin deformation on the perception of illusory pulling by presenting vibratory stimuli to a fixed fingertip, so as to minimize proprioceptive input. Psychophysical experiments combined with GLMM analysis suggested that peak asymmetries in position and velocity were the primary contributors to the illusion. This finding differs from previous work using similar stimuli [1], possibly due to the suppression of proprioceptive cues resulting from finger fixation in our setup. Merkel cells and Meissner corpuscles—cutaneous mechanoreceptors sensitive to the frequency range used in this study—are thought to encode skin deformation and its velocity [3], making our results consistent with known physiological mechanisms of tactile processing. Future work will compare results under grasping conditions to assess cutaneous vs. proprioceptive contributions to the illusion.

References

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