Exploration of the Correlation Between the Dynamic Behavior of the Skin and Vibrotactile Perception

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Abstract

Vibrations are frequently used for haptic feedback in wearable devices, such as notifications or action prompting. Recent studies have shown that vibrating stimuli can create waves that spread widely throughout the skin, with amplitudes exceeding the perception threshold. However, the relationship between the propagation of stimulation and the thresholds of vibrotactile perception remains to be investigated. This paper presents the results of the skin dynamics and demonstrates the relationship between distance-averaged attenuation and perception parameters. The data suggests a strong negative correlation between just noticeable difference and distance-averaged attenuation, particularly for frequencies around 300 Hz. This relationship can guide the arrangement of actuators to optimize vibrotactile feedback.

Introduction

The human skin perceives the environment through physical contact. Haptic feedback technologies can deliver touch information by exerting force, heat, or vibrations on the skin. Vibrotactile feedback is a highly favorable option for creating human-machine interfaces due to the relative lightweight and compact design of vibration actuators and the wide information bandwidth they provide. Vibrotactile feedback has a wide range of use cases, including notifications and action prompting for wearables, as well as texture rendering [1] and developing touch illusions [2] in virtual reality.

The vibrotactile sensation is mediated by a large group of mechanoreceptors widely distributed in the skin. Pacinian corpuscles (PCs) are mechanoreceptors that are exquisitely sensitive to vibrations from 40 to 400 Hz and have a large receptive field [3]. Upon receiving vibration signals, the PCs produce neural spikes that transmit tactile information to the central nervous system. The sense of touch is produced by a spatiotemporal integration of the tactile information. Thus, the efficacy of vibrotactile feedback depends on the careful management of the vibration patterns generated on the skin [4].

In practical applications, an ensemble of vibration actuators is often used to create richer patterns on the skin and increase the amount of information in the feedback. However, the ideal arrangement of vibration actuators is unclear, especially considering the different sensitivities of different body regions [5, 6] and the involvement of complex skin dynamics [7]. Even when stimulating the skin with a single actuator, vibrations can propagate from the contact point of the exciter to distant areas and stimulate a large area of the skin. Although the amplitude of the vibrations decreases proportionally with increasing distance [8], skin in remote regions can still receive the information encoded in the vibration signals [9]. Indeed, within certain frequency bands, the skin has a remarkably low vibrotactile detection threshold (10 µm at 250 Hz) [10, 6], allowing it to perceive even weak vibrations that have traveled considerable distances. Therefore, to better understand how the placement of vibration actuators on the skin affects the resulting vibrotactile feedback, the perceptual effect of skin vibration propagation needs to be clarified.

Here, we seek to elucidate the relationship between the perceptibility of vibrotactile feedback and the degree of vibration propagation along the forearm. Using laser vibrometry, we first characterized the damping behavior of skin vibrations through in vivo measurements from 11 subjects. We determined their absolute detection thresholds and the just noticeable difference (JND) of skin vibrations through psychophysical experiments. We then investigated the interaction between the observed attenuation of skin vibrations and the corresponding vibrotactile perceptual factors.

Experimental Setup

An experimental setup (see Fig. 1) was created to meet the requirements outlined in the previous section. The setup comprised a measurement frame, a B&K Type 4810 shaker as the vibration source, a Polytec VGO 200 laser Doppler vibrometer (LDV), and a reflective mirror (Thorlabs BB1-E02). The area of interest was the bottom of the forearm, which is a large smooth area of human skin and allows for easy distance measurement from the vibration source. A support frame was created to ensure the subject's comfort during measurements. The frame has dimensions of 750×300×250 mm and provides three support points via crossbars: two for the palm and one for the elbow. The elevation is necessary for mounting the laser vibrometer and reflection system. The crossbars and longitudinal beams can be adjusted upon the subject's request. This setup allows the subject to sit without moving and relax their forearm muscles.

The shaker amplitude was set to 10 dB above the reference perception threshold. It was mounted upside down and connected to a counterweight via a metal string

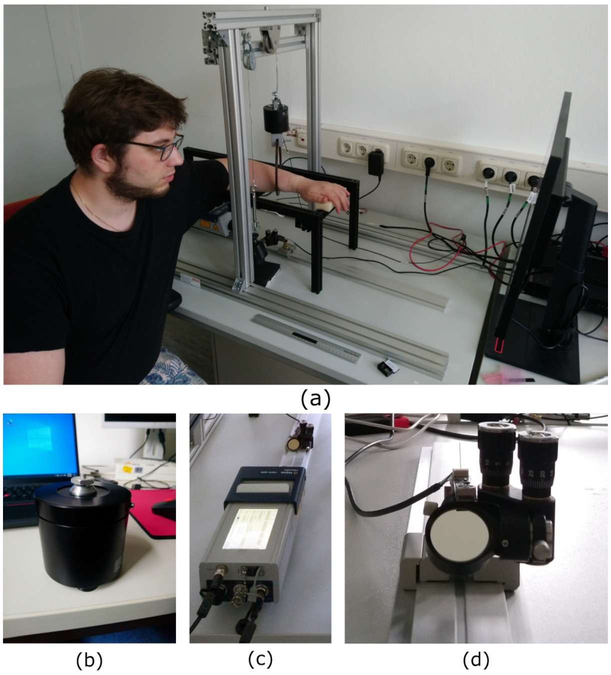


Figure 1: Experimental setup for characterizing the dynamics of the skin's reactions to vibrotactile stimulation. The setup includes a support frame (a), a plywood ring driven by a B&K Type 4810 shaker (b) as a vibration source, a laser vibrometer (c) to measure skin vibrations, and a reflective mirror (d) to redirect the laser to adjust measurement locations. Participants inserted their forearms into the plywood ring, which produced skin vibrations on contact. A counterweight pulling the shaker helped maintain a constant contact force throughout the measurement.

through a pulley block. The shaker weighs 1.3 kg, and the counterweight weighs 1.5 kg. This weight distribution creates an upward force through force-directed movement. The participants' skin was stimulated with vibrations using a plywood ring connected to a metal connector and a cylindrical 8 mm diameter contact pin made of PETG. To apply the stimulation, the participant inserted their hand into the ring and placed the middle point of their forearm onto the contact pin. The system maintained a pressure of 39 kPA on the subject's skin.

The laser vibrometer and reflective mirror are mounted on a dovetail rail using a clamping platform. This is necessary to avoid measurement errors. The data from the laser vibrometer is transferred in a text file to a computer connected to the LDV via an Ethernet cable. A visualization of the raw data sample is shown in Figure 2 (a). MATLAB code was written to convert this information into the frequency-velocity format. The conversion script segments the frequency, highlights the envelope of each frequency segment, and calculates the average amplitude data at each frequency (see Figure 2 (b)). This velocity data is used for further analysis.

Skin Attenuation Measurement

The experiment involved eleven participants (8 males and 3 females) between the ages of 22 and 39. Skin attenuation was measured at 11 frequencies ranging from 24.8 Hz to 316 Hz, ordered by a 1/3 octave band. Skin attenuation was measured at distances ranging from 5 mm to 25 mm from the stimulus source, with a 5 mm step. The measurements were taken to determine the degree of skin absorption at varying distances. Each measurement block represented a fixed distance point across frequencies. The frequency array was repeated 5 times, with elements randomly shuffled. Each frequency step lasted 1.5 seconds with a one-second interval between them. The skin vibration attenuation factor was calculated using the following equation:

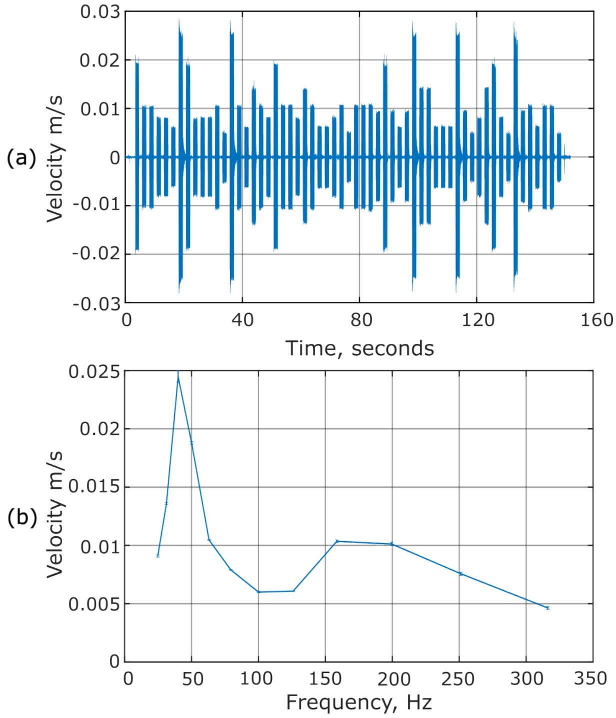


Figure 2: An example of skin vibration measurement resulting from sinusoidal stimulation with randomly shuffled frequencies ranging between 25 and 316 Hz. (a) The raw data was obtained from LDV. For analysis, use the velocity over frequency format shown in (b), which is a result of segmenting and averaging the amplitude of the frequency steps from (a).

$$Attenuation = 20 \cdot log_{10}(\frac{A_{in}}{A_{out}})[dB]; \qquad (1)$$

where A_{in} is the measured skin vibration velocity next to the vibration source while A_{out} is the vibration velocity measured at the distanced locations along the forearm.

The skin vibration attenuation was averaged across participants and plotted against the quantiles Q1 - Q3 (see to Fig. 3). The results show that the attenuation of skin vibrations increases with distance and is frequency-dependent. As the frequency increases from 50 Hz to 316 Hz, the attenuation increases, resulting in a fading of the vibrations. Furthermore, we observed that attenuation varied non-monotonically across frequencies: decreasing slightly from 25 to 50 Hz and increasing substantially from 50 to 310 Hz. This pattern is stronger at higher levels of attenuation.

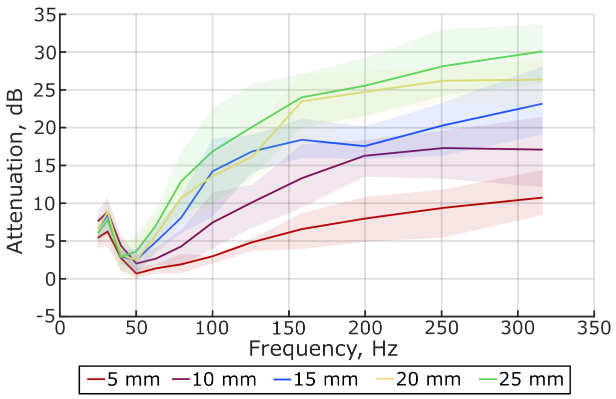


Figure 3: Attenuation of skin vibrations traveling across the forearm. The amplitude of the stimuli was measured within the frequency range of 25 Hz to 316 Hz. Attenuation is defined as the ratio between the input amplitude and the measured stimuli amplitude on the participants' skin. The colors used in the graph correspond to different levels of attenuation, ranging from 5 mm to 25 mm. The shaded area represents the quantiles Q1 - Q3.

Psychophysical Experiments

We assessed the absolute perception threshold and JND of vibrotactile feedback using the same setup as described above. The absolute perception threshold refers to the minimum amplitude level that a participant can detect, while JND is the minimum amplitude difference that participants can distinguish in comparison to a reference level. Each measurement lasted between 20 and 30 minutes, with a 10-minute break between them. Both measurements used a 1-up 3-down staircase rule. The measurement of the perception threshold involves two alternated forced choices, while the measurement of the JND involves three interval forced choices. The staircase procedure comprises 25 to 30 rounds, and the final levels are determined by averaging the amplitudes of the last 4 rounds. The procedure is repeated for five frequencies, which are ordered from the 1/3 octave band: 25 Hz, 50 Hz, 100 Hz, 158 Hz, and 316 Hz. The experiment employs a two-second sinusoidal signal as stimuli.

The frequency dependencies of psychophysical parameters were obtained, averaged across participants, and plotted alongside the quantiles Q1-Q3 (see Fig. 4). The perception threshold is highest in the low-frequency area (refer to Fig. 4(a)). The frequency threshold decreases up to 158 Hz and then increases again. Participants are more sensitive to vibrations between 100 and 158 Hz. This behavior aligns with previous studies [10, 11]. JND refers to the smallest detectable change in a stimulus. JND is highest at 50 Hz and lowest at 25 Hz. This means that participants can detect much smaller differences above the reference vibration level at 25 Hz compared to other frequencies.

Correlation Between Skin Attenuation and Psychophysical Parameters

Pearson's correlation coefficient r is used to find the correlation between perceptual and skin dynamic parameters. The following equation calculates Pearson's r [12]:

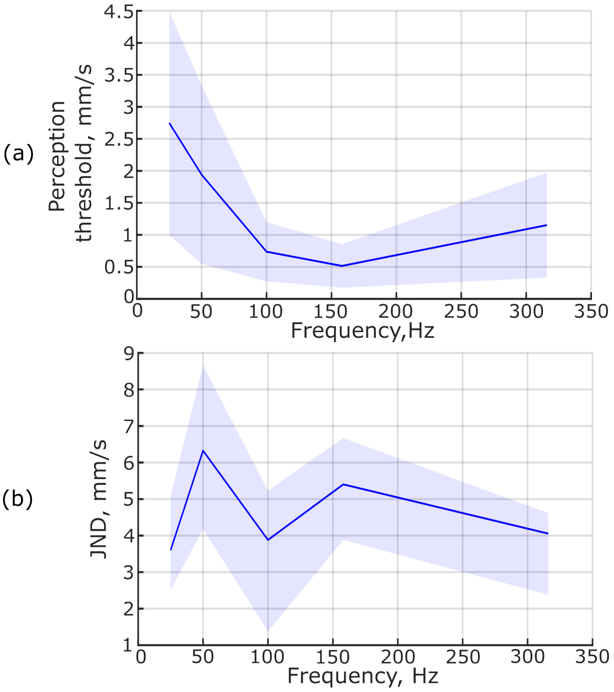


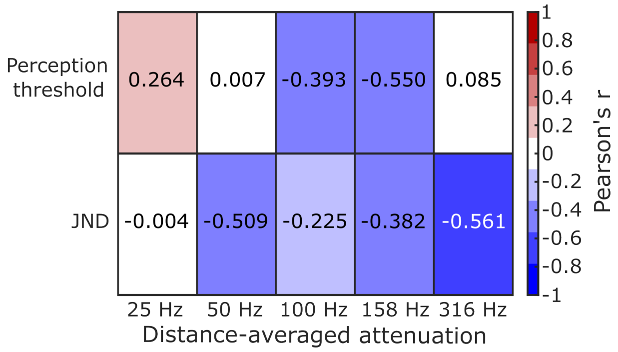
Figure 4: Results of the psychophysical experiments. (a) Frequency dependence of perceptual threshold. (b) Frequency dependence of JND. The psychophysical parameters were measured at 6 frequencies ranging from 25 to 316 Hz. The 1-up 3-down staircase rule was used for the measurement. The shaded area corresponds to the quantiles Q1 - Q3.

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}; \tag{2}$$

where r - Pearson's correlation coefficient; n - number of parameters in vectors; x and y - compared variables.

The Pearson correlation coefficient ranges from -1 to 1. A correlation of 0.5 or higher is considered strong, regardless of the sign. A correlation between 0.5 and 0.3 is moderate, while a correlation between 0.3 and 0 is weak. A correlation of 0 indicates no correlation. The sign indicates the direction of the correlation. For example, in a positive correlation, as the value of x increases, the value of y also increases. In a negative correlation, as the value of x increases, the value of y decreases. In our case, x represents a perception parameter, while y represents the average attenuation across the distance from the vibration source. The calculation is repeated for each frequency within the range of frequencies used in the psychophysical experiments.

The calculated Pearson's r was inserted into the heatmap (see Fig. 5). It indicates a strong correlation between the perception threshold and distance-averaged attenuation at 158 Hz. A moderate positive correlation is observed at 25 Hz and a moderate negative correlation at 100 Hz. However, there is no correlation between the perception threshold and distance-averaged attenuation at 50 Hz and 316 Hz. Additionally, there is no correlation between JND and distance-averaged attenuation at 25 Hz. There is a strong correlation at 50 Hz and 316 Hz, and a moderate correlation at 100 Hz and 158 Hz.



	25 Hz	50 Hz	100 Hz	158 Hz	316 Hz
Perception threshold	0.264	0.007	-0.393	-0.550	0.085
JND	-0.004	-0.509	-0.225	-0.382	-0.561

Figure 5: Matrix whosing correlations between perception parameters and the distance-averaged attenuation factor across frequencies. Each cell in the table represents a calculated correlation factor between one of the perception parameters and the averaged attenuation across the distance at a specific frequency.

Conclusions

Skin attenuation level, perception threshold, and just noticeable differences were measured using laser vibrometry to investigate the relationships between these parameters. An experimental setup and procedure were developed to allow for skin dynamic measurement, as well as psychophysical experiments. Skin attenuation was measured at frequencies ranging from 25 Hz to 316 Hz and distances ranging from 5 mm to 25 mm. The study characterized the attenuation behavior of skin vibrations and confirmed prior findings that the vibration propagation distance decreases with increasing frequency [8, 13, 14]. Psychophysical parameters were measured at five frequencies ranging from 25 Hz to 316 Hz. The measured vibration perception threshold also aligned with prior research, which identified the skin's highest sensitivity in the vicinity of 100 Hz to 150 Hz [10, 11]. The study found a significant correlation between the vibration perception threshold and the distance-averaged attenuation of skin vibrations at 158 Hz. However, the correlation between the JND and skin vibration damping was less than -0.22 from 50 to 316 Hz. Notably, a strong negative correlation (< -0.5) was observed between JND and distance-averaged attenuation at 50 Hz and 316 Hz. This relationship could guide the arrangement of actuators to improve vibrotactile feedback performance. Furthermore, since tactile perceptual thresholds for vibrotactile stimuli at the range of 60 to 500 Hz across the adult lifespan [11], effects of age on the relation between JND and skin dynamics need to be further investigated for developing age-inclusive haptic actuation [15].

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