Pseudo-Frequency Modulation: A New Rendering Technique for Virtual Textures

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Abstract. Creating virtual textures with speed-invariant identities requires spatial constancy, attained by changing temporal frequency with a finger's sliding speed. Implementing sensations of continuous frequency change, however, is non-trivial for low-cost wearable vibrotactile displays, as the amplitude of commonplace voice coil motors and linear resonant actuators varies strongly with driving frequency. In this paper, we present Pseudo-Frequency Modulation (PFM), a technique to continuously change the perceived frequency by modulating only the amplitudes of two single-frequency components in response to changes in sliding speed. Results of a psychophysical study with a wrist-worn vibrotactile display show that people perceive smooth changes in frequency with PFM, and this technique can be reliably used to display distinguishable textures which differ in terms of perceived surface properties such as coarseness.

Keywords: Vibrotactile display · Perception and psychophysics · Virtual reality

1 Introduction

Diverse texture rendering can add a new dimension to virtual experiences by producing a wide range of distinguishable haptic sensations. In this work, we seek to preserve both a diversity of texture sensations and a fundamental perception of "texture" (rather than "buzzing") using as simple as possible vibrotactile rendering. Our technique continuously modulates a perceived temporal frequency in response to finger sliding speed. This is done in order to preserve spatial constancy [8] and realism [3] when actively exploring a virtual texture. While actual preservation of spatial constancy requires continuous changes in temporal frequency, our technique is significantly simpler. It renders continuous shifts in perceived temporal frequency by superimposing two single-frequency components and modulating only their vibration *amplitudes* as a function of user's sliding speed [13].

A vibrotactile texture display provides direct vibration to the skin as a substitute for texture-elicited skin vibrations. A real textured surface has a spatial frequency, defined by the spacing between its individual asperities. A uniform texture, for example, would have a constant spatial frequency in a given direction. When we slide our skin across such a real textured surface, contact with surface asperities evoke vibrations in our skin. These vibrations have a temporal frequency, which depends not only on the texture's spatial frequency, but also on our sliding speed [8]. These temporal changes in skin vibrations form the basis of our texture perception. If a real texture has a constant spatial frequency, our perception of its identity also remains constant regardless of our sliding speed [2]. At the neural level, our sense of movement is fused with a proportional change in the temporal frequency of the texture-elicited vibration, preserving spatial constancy. Extending this understanding of texture perception to virtual environments, vibrotactile feedback provided by texture displays should also respond dynamically to the user's speed by proportionally changing the temporal frequency.

Many previous studies have employed this speed-responsiveness in texture displays. For example, Konyo *et al.* [12] continuously modulated the vibration frequency in response to the hand velocity. However, they had to continuously apply phase adjustments to produce smooth frequency-modulated outputs. Similarly, rendering of a coarse texture was perceived as more real when frequency was continuously modulated as a function of the sliding speed [6]. Here, the driving voltage to the broadband Voice Coil Motor (VCM) had to be filtered to achieve matched displacement amplitude at all the frequencies. This was necessary to compensate for the non-flat frequency response of a VCM. Such examples are evidence for high real-time processing demands of continuous frequency modulation.

Researchers have also explored data-driven techniques to achieve high realism in texture rendering. They recorded acceleration signals while actively exploring a real texture to generate texture models. These models were used to synthesize vibration signals as a function of user's normal force and sliding speed. These techniques, however, have only been assessed for tool-texture interactions; further, it requires extensive data acquisition and processing for generation of texture models [4, 24].

Aiming to simplify the process of texture rendering, while preserving a fundamental perception, we looked at superimposed vibrations. In a past study, it was shown that superposition of two frequency components is perceived as a single pitch equivalent, where the pitch equivalent correlates to the amplitude ratio of individual single-frequency components [5]. Therefore, to circumvent the real-time processing demands of continuous frequency modulation, we asked: can we continuously modulate a perceived frequency by using superposition of just two single-frequency signals?

Indeed, superimposed vibrations have been considered previously in texture rendering [12]. Researchers have also used dual-frequency vibrations in audio-to-haptic conversion with the same principle of reducing the amount of information while still preserving a basic expression [10, 15]. Some studies have extensively characterized the perceived properties of dual-frequency vibrations for hand-

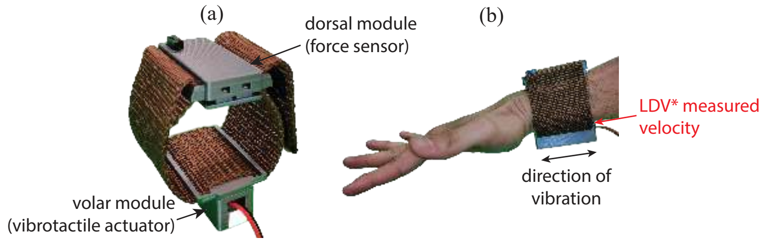

Fig. 1. (a) Wrist strap with two 3D printed modules in gray. The volar and dorsal modules house the vibrotactile actuator and the force sensor, respectively. (b) A user wearing the wrist strap and actively exploring a virtual texture in mid-air using their index fingertip. The directions of actuator vibration and LDV measured velocity are also shown. (*LDV: Laser Doppler Vibrometer)

held vibrotactile devices [11, 29]. However, to our knowledge, none have used superimposed vibrations to preserve spatial constancy of virtual textures.

Based on these observations, we propose a technique to continuously modulate the perceived frequency of a vibrotactile display as a function of finger sliding speed. We are initially exploring the simplest possible signals, two superimposed sinusoids, but anticipate studies with more complex vibrations in the future. The key contributions of this work include (1) an experimental setup to evaluate vibrotactile signals in wrist displays, and (2) preliminary results which validate the use of two single-frequency components to continuously modulate the perceived frequency and preserve spatial constancy.

2 Methods

2.1 Wrist Strap Design

The desired form factor of a tactile display is a critical early design decision. Wearable vibrotactile displays can be broadly classified into two types. The first renders sensations directly to the fingertips and takes the form of thimbles [27] and gloves [9, 23]. The second relocates feedback to proximal body sites, e.g. the ventral side of the distal [17] and proximal phalanx [6, 25] or around the wrist [7, 21]. While lower tactile acuity could be a drawback of relocating sensation away from the fingertips [7, 14], relocating feedback remains of interest as it frees the fingertips to dexterously interact with the real world objects in augmented or mixed reality applications. A wrist form factor, in particular, offers low occlusion of the hand, which improves seamless hand tracking using camera-based trackers. It also allows the use of larger broadband actuators due to increased real estate on the wrist. Additionally, changes along the roughness-smoothness dimension can still be encoded via changes in frequency at locations away from the fingertips, including the wrist [7]. Based on these considerations, we designed a wrist strap. It accommodates two components: an actuator to facilitate vibration, and a

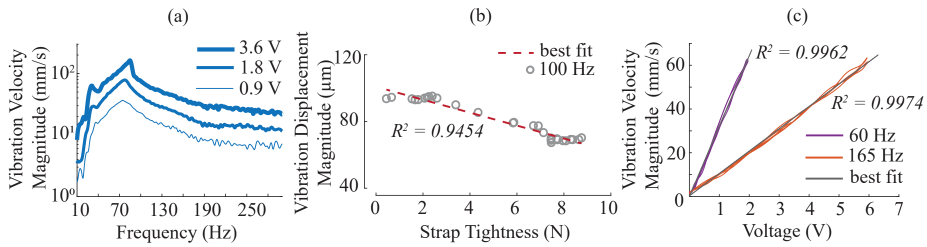

Fig. 2. (a) Frequency response of the wrist strap actuated by a Voice Coil Motor (VCM). The vibration intensity is strong for a broad range of frequencies, but the response does not exhibit a flat characteristic. (b) Effect of strap tightness on displacement magnitude of a 100 Hz vibration - evidence for the need to ensure consistency of strap tightness in psychophysical experiments. (c) The relationship between measured vibration velocity magnitude and actuator input voltage is linear up to 2 V and 6 V for 60 Hz and 165 Hz signals, respectively, as shown by the lines of best fit. The vibration velocity magnitude of both the single-frequency components was kept under 36 mm/s, and hence in the linear range.

force sensor to monitor the strap tightness. These components are housed in 3D printed modules, as shown in Fig. 1a.

Vibrotactile Actuator The volar module consists of a vibrotactile actuator and a cover, both snap-fitted to a base plate. The module's position can be adjusted along the strap to accommodate for different wrist sizes. The actuator vibrates parallel to the skin, in the distal-proximal direction, as shown in Fig. 1b. These vibrations are transmitted to the volar skin through the base plate and the strap. We chose the volar side for tactile feedback due to its higher tactile acuity than the dorsal side [1, 16, 19]. Additionally, this keeps feedback on the same side of the forearm as the finger pad, where sensations will appear to occur during virtual interactions. We selected a VCM (Hapcoil-One, Actronika) for vibrotactile actuation owing to its strong vibrations at a broad range of frequencies. Fig. 2a shows the non-flat frequency response of the strap, obtained by playing a chirp (10 Hz to 300 Hz) on the actuator at three different voltage levels. All vibration measurements were made in the direction of the actuator vibration using a single point Laser Doppler Vibrometer (LDV Polytec VFX-F-110, VFX-I-160 sensor head). The strap was worn with a tightness of 2.6 N and the laser was focused at the strap edge, which directly contacts the volar side, as depicted in Fig. 1b. Data was acquired using National Instruments USB-6211 at a sampling rate of 10 kHz, and high pass filtered with a 20 Hz cutoff frequency to remove variations caused by low frequency hand tremors.

Force Sensor The dorsal module monitors the strap tightness, which is known to affect the vibration amplitude of a wearable [22]. Inspired from Tasbi [21], it has a circular capacitive force sensor (SingleTact CS15-4.5N), held in place by

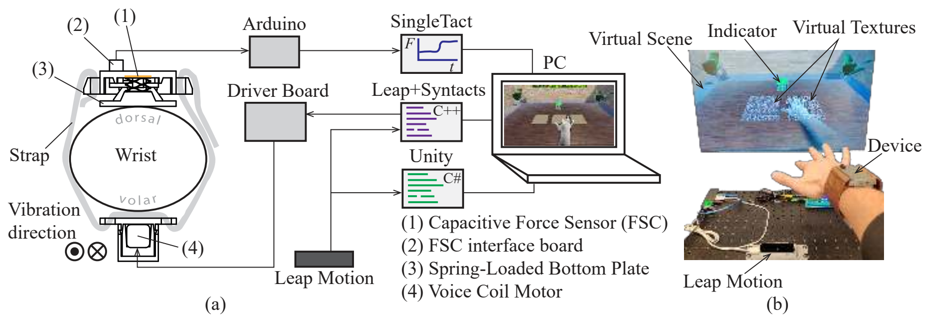

Fig. 3. (a) Schematic of the setup showing the wrist strap's cross-sectional view, subcomponents, and peripherals. (b) Picture of a participant wearing the wrist strap and exploring a virtual texture. A virtual scene is also shown on a screen which contains textures and a real-time hand animation, rendered via hand tracking using Leap Motion.

a pre-compressed disc spring. The spring is attached to a movable plate, which is in direct contact with the wrist as shown in Fig. 3a. An increase in strap tightness pushes the plate, compresses the spring, and generates a measurable load on the force sensor. To calibrate the force sensor, we removed the volar module, applied known pull forces to the volar strap worn on the wrist, and measured the force response. Fig. 2b shows the effect of strap tightness on the displacement magnitude of a 100 Hz vibration. This provides further evidence for the need to ensure fit consistency during psychophysical experiments.

2.2 Virtual Environment

We acquired index fingertip position data—streamed from a Leap Motion Controller (a stereo camera for hand tracking from Ultraleap) at 120 Hz—to calculate the instantaneous speed at each frame. We then considered six consecutive frames to obtain a weighted moving average and modulated the vibration signals as a function of this average speed (in a C++ application).

We used Leap Motion's Unity plug-in to render a real-time hand animation in virtual environments. These environments included virtual texture surfaces and an indicator light which turns green to indicate user's presence in the texture's interaction zone, as shown in Fig. 3b. The two-dimensional size of each interaction zone differed across the virtual environments; but the height was set to a constant 75 mm, with the texture surface at its center. This gave the users flexibility to deviate slightly from the plane of the texture and still remain in touch with the virtual mid-air textures. We entered the dimensions of each interaction zone manually in both the C++ and Unity applications to toggle the actuator and the virtual indicator, respectively.

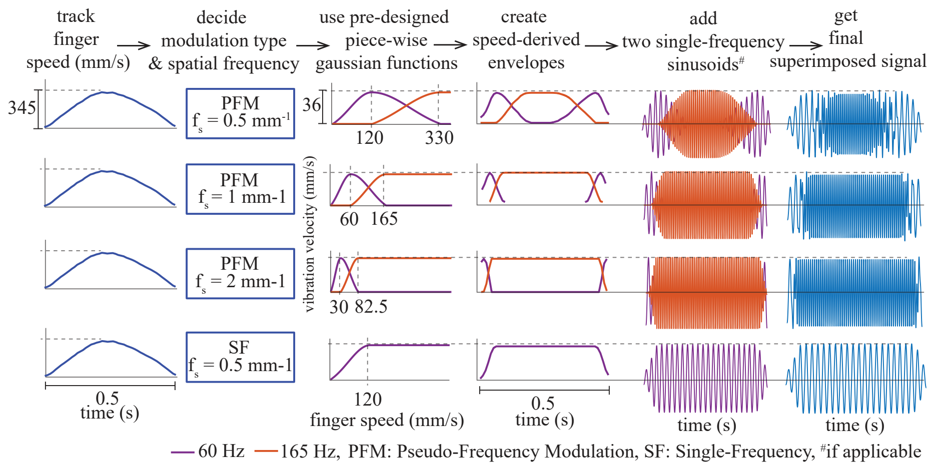

Fig. 4. Signal design procedure for Pseudo-frequency modulated (PFM) and single-frequency (SF) textures used in this study. The PFM signals were designed for three distinct spatial frequencies: 0.5, 1, and 2 per mm. The single frequency signal was designed for only 0.5 per mm.

2.3 Signal Design

To modulate vibrotactile feedback as a function of a user's finger speed, we need to generate a speed-dependent signal. We achieved this by integrating Leap Motion and Syntacts (an open-source software from Rice University [20]) in a single C++ application. We customized the spatializer feature of Syntacts to modulate the amplitude of sinusoidal audio signals. The processed audio signals were converted to Pulse Width Modulated (PWM) signals by a multichannel H-bridge driver board (HSD Mk 1, Actronika) which outputs an amplified signal to power the actuator.

Fig. 4 outlines the proposed signal design using a combination of 60 Hz and 165 Hz vibrations. We selected this combination from many possible choices, wherein the amplitudes can be matched without overloading the actuator. During pilot studies, we observed that the proposed technique is more effective with such a fluttery-smooth combination i.e. low frequency in 10-70 Hz range and high frequency above 150 Hz [26]. To predict the physical amplitude of the vibration as a function of the input voltage, we obtained the voltage characteristics by measuring the vibration response to a sinusoidal input voltage at each of the two frequencies. Fig. 2c shows that the relationship between vibration velocity magnitude and input voltage is linear up to 2 V and 6 V for 60 Hz and 165 Hz signals, respectively.

Pre-designed piecewise gaussian functions, shown in Fig. 4, are the main component of the proposed signal design for a given design spatial frequency f_s. In the context of our signal design process, spatial frequency is just a design parameter; our intent is to create distinguishable textures, and not to perfectly mimic the textures with such physical spatial frequencies. At sliding speed s under a threshold speed value s_1, we only modulate the 60 Hz vibration as a function of speed, which then saturates to a set level A. As the speed increases further, the amplitude of 60 Hz vibration diminishes, while the 165 Hz vibration ramps up to the set level at the same rate, which is defined by a second threshold speed s_2. Speeds higher than the second threshold will only produce set level 165 Hz vibration. This technique will hereafter be referred to as Pseudo-Frequency Modulation (PFM).

These gaussian functions involve two important design decisions: (1) threshold sliding speeds (s_i, $i = 1, 2$) and (2) the set level or matched maximum vibration amplitude (A). The threshold sliding speed s_i for each single-frequency component is simply the ratio of the temporal frequency f_t and the desired spatial frequency f_s. For example, for a desired spatial frequency of $0.5\,\mathrm{mm}^{-1}$, the threshold sliding speeds are 120 mm/s and 330 mm/s for 60 Hz and 165 Hz components, respectively. The matched maximum vibration amplitude A could be the amplitude of displacement, velocity, or acceleration. Greenspon *et al.* [8] found that the displacement of texture-elicited vibrations remains constant with the sliding speed. Displacement matching, however, posed a challenge due to the reduced frequency response of the actuator at higher frequencies (Fig. 2a). At actuator-safe input voltage levels, a 60 Hz vibration, displacement matched with a 165 Hz vibration, is perceptually weak. Therefore, we chose to match the velocity amplitudes, with $A = 36$ mm/s, which is in the linear range of the voltage characteristics shown in Fig. 2c. We designed three gaussian functions for design spatial frequencies $f_s =$ 0.5, 1, and $2\,\mathrm{mm}^{-1}$. Eq. (1-2) show the mathematical expressions for the designed gaussian functions. Here F is a gaussian function that depends on tracked finger speed s, threshold speed s_i, and a variable c. G_1 and G_2 are piecewise gaussian functions (formulated using F) for 60 Hz and 165 Hz components, respectively.

$$F(s, s_i, c) = 0.25A[5e^{\frac{-(s-s_i)^2}{2s_1^2c^2}} - 1] \tag{1}$$

$$G_i(s) = \begin{cases} G_1 = F(s, s_1, 0.55),\ G_2 = 0 & s \le s_1,\ c = 0.55 \\ G_1 = F(s, s_1, 0.97),\ G_2 = F(s, s_2, 0.97) & s_1 < s \le s_2,\ c = 0.97 \\ G_1 = 0,\ G_2 = A & s > s_2, \end{cases} \tag{2}$$

Using these piecewise gaussian functions G_i in conjuction with tracked finger speed s provides speed-derived envelopes in time domain. We also designed a single frequency signal of 60 Hz vibration, corresponding to a $0.5\,\mathrm{mm}^{-1}$ spatial frequency, for comparison with PFM, as shown in Fig. 4.

3 Psychophysical Experiments

We conducted a psychophysical study (TAMU IRB2022-1042) with 15 participants (one left-handed, seven women, ages 18-34). Participants wore the device on their dominant wrist with a strap tightness of 2.6 N. We instructed them to keep all fingers extended with an open hand posture while exploring the virtual textures, since gestures also affect strap tightness. Pink noise was played through a pair of noise cancelling headphones to mask any audio from the actuator. The experiment spanned two preliminary training tasks followed by four subsequent experiments. Only Experiment 4 had a visual representation of textural features overlaid on the haptic vibrotactile feedback. For all the prior experiments, participants saw only a blank gray surface.

3.1 Training

The objective of these tasks was to introduce participants to the concepts of amplitude and frequency and to assess if they can correctly describe changes in these properties. In the first task, we played a sequence of three distinct single-frequency vibrations on the actuator, each with a different amplitude (30, 50, and 90 μm displacement) but same frequency (100 Hz). We then asked participants to assign labels of low, mid, and high based on the amplitude. The second task involved the same procedure, but the vibrations differed in terms of frequency (60, 120, and 240 Hz) at a constant voltage of 1.8 V (the actuator's frequency response determined the amplitude at each of the three frequencies). Each task consisted of 3 trials per participant (total 45 trials), and the sequence was randomized in each trial. We used simple terms to describe vibration properties to non-STEM participants, e.g. 'loudness' or 'intensity' for amplitude and 'how fast' for frequency.

Results Fig. 5a demonstrates that low, medium, and high amplitudes were correctly identified by almost all participants. When identifying vibrations of different frequency, a subset of participants (3 out of 15) consistently confused high and low frequency values and reported them in the reverse order. Post-training queries indicate that these participants focused only on amplitude.

3.2 Experiment 1: Detection of PFM

Experiment 1 consisted of a 30 cm square texture slab at the center of the virtual environment. We asked participants to practice sliding their finger across the virtual texture in mid-air while being consistently in 'touch', signaled by a green indicator. After necessary practicing, we displayed PFM $f_s = 0.5\,\mathrm{mm}^{-1}$ on the virtual texture slab through the actuator. We then asked participants to slide their fingers in circular motions, spanning the entire square texture slab and at a constant speed, regulated using a metronome. After repeating the procedure for three different speeds (with 40, 69, and 100 beats per minute; 2 beats per circular motion), we asked participants if they sensed a change in the vibration between the three speeds; if yes, then which of two properties changed—frequency or amplitude.

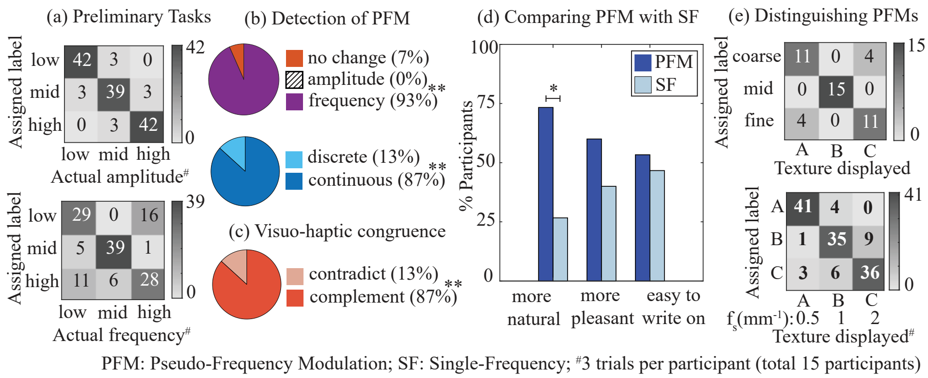

Fig. 5. Results for psychophysical experiments: (a) Preliminary tasks demonstrate ability of participants to discern changes in amplitude and frequency. (b) Experiment 1 shows that participants perceived a continuous change in frequency with PFM. (c) Addition of visuals complemented the haptic texture feedback. (d) PFM is significantly rated as more natural. (e) Participants accurately identified the trend of changing coarseness and distinguished three different PFM textures made with just two single-frequency components. Statistically significant results are marked with asterisks; * and ** mean *Z-test* $p < 0.05$ and $p < 0.01$, respectively.

Results Fig. 5b shows that 14/15 participants sensed a change in frequency ($Z\text{-}test, p = 0.0004$). When asked to gradually increase their speed in a single circular motion on the virtual texture, 13/15 participants sensed a continuous change in frequency ($Z\text{-}test, p = 0.0023$).

3.3 Experiment 2: Comparing PFM with Single Frequencies

Experiment 2 consisted of two 22.5 cm square texture slabs placed side by side. We displayed PFM on one and a single frequency vibration of 60 Hz on the other slab (both corresponding to $f_s = 0.5\,\text{mm}^{-1}$). The placement order was randomized for each participant. We allowed the participants to actively explore each texture without any speed or time constraints, and asked them which texture feels more natural and pleasant. We also asked them to write invisible alphabets like 'P' or 'M' on each slab using their index finger and choose which texture requires less cognitive effort, i.e. which was easier to write on.

Results Fig. 5d shows that the participants rated PFM texture as more natural ($Z\text{-}test, p = 0.0349$). While the other two ratings were also higher for PFM, the difference is insignificant.

3.4 Experiment 3: Distinguishing PFMs

Experiment 3 consisted of three 15 cm square texture slabs placed side by side, as shown in Fig. 3a (see PC). First, we displayed PFM $f_s = 0.5\,\text{mm}^{-1}$, $1\,\text{mm}^{-1}$

and $2\,\mathrm{mm}^{-1}$ on texture slabs left to right, and named them Texture-A, B, and C. We asked participants to get familiar with each of the three textures by active exploration, and arrange them in increasing order of coarseness. Next, we randomized the placement order of these three textures and asked participants to identify and assign labels of A, B, and C, from their memory of each texture. The texture identification task was repeated for 3 trials per participant (total 45 trials).

Results The top confusion matrix in Fig. 5e shows that participants accurately identified the trend of changing coarseness. However, some confusion occurred between most and least coarse textures due to difference in the notion of coarseness for a few participants. The bottom confusion matrix in Fig. 5e shows that the participants accurately identified each of the three virtual textures, which differed in terms of design spatial frequency.

3.5 Experiment 4: Visuo-haptic congruency

Experiment 4 consisted of two 22.5 cm square texture slabs. The left and right slabs had a haptic display of PFM $f_s = 0.5\,\mathrm{mm}^{-1}$ and $1\,\mathrm{mm}^{-1}$, and a visual display of spatial frequency $1\,\mathrm{cm}^{-1}$ and $2\,\mathrm{cm}^{-1}$, respectively. We adopted an order of magnitude higher spatial frequency in visual display to make it easy for the participants to visually distinguish the textures. The participants compared the two slabs by active exploration, and we asked them if the visual representation complements or contradicts the vibrotactile haptic display.

Results Fig. 5c shows that the visual representation had complemented the haptic display for 13/15 participants ($Z\text{-}test, p = 0.0023$).

4 Discussion

In this study, we proposed Pseudo-Frequency Modulation (PFM), a technique to continuously modulate the perceived temporal frequency as a function of finger sliding speed by only modulating the *amplitude* of two single-frequency components. We then conducted a psychophysical study to assess the effectiveness of PFM in preserving spatial constancy. To our knowledge, this is the first assessment of such a technique, and hence we implemented a minimal signal design using a single combination of pure sinusoids to prove the concept.

We found that participants overwhelmingly detected a continuous change in frequency with variations in their sliding speed on a PFM texture. When compared to a single frequency (SF) texture, they rated PFM as more natural, associating it with real textured surfaces e.g., tarp, velcro, breadboard, etc. Some participants emphasized that PFM feels the same everywhere i.e., uniform. Participant preference for the SF texture in the pleasantness task, however, may be due to its lower vibration frequency.

During pilot studies, early participants reported greater control over their motion on PFM textures. This allowed them to perform tasks like writing with higher accuracy, which informed our design of Experiment 2. Conversely, the results of the writing task in Experiment 2 did not show a significantly better rating for PFM textures. This could owe to task comprehension issues e.g., some ratings were given based on coarseness under the assumption that larger coarse features are easier to write on.

We also found that participants can reliably distinguish three PFM textures even though they are composed of the same single-frequency components. This has implications for the success of diverse virtual texture designs using only two single-frequency signals, either with broadband VCMs or by using two tiny LRAs with distinct resonant frequencies placed within the two-point discrimination threshold [18]. Finally, visual representation of textural features complemented the PFM based vibrotactile display, suggesting the potential of integrating PFM with visual feedback. Some participants emphasized that while they can describe texture coarseness even without the visuals, the process of distinguishing textures becomes faster with a visual representation.

Nevertheless, the findings of this study are limited to simple sinusoidal single-frequency vibration components. The range of possible diverse textures is also limited with just two single frequency components. More complex signal combinations can potentially create sensation of properties other than coarseness, e.g. stickiness, adding to the diversity. In addition, Leap Motion's low sampling rate and actuator's slow dynamic response contribute to the latency of the system, thereby impacting the realism of the haptic feedback. Faster hand tracking solutions and actuators with improved dynamic response may help alleviate such latency issues in the future. The psychophysical study is also limited in terms of its categorical data, and the use of numeric ratings may help in better quantification of conclusions made in this study. Lastly, the results are limited to wrist displays and the effectiveness of the technique remains unexplored at the fingertips. Considering similar frequency discrimination performance between the two body sites [16] (despite marked differences in detection thresholds), the technique may translate to the fingertips as well.

In the future, we will build on this experimental platform by improving the latency. We will do a comprehensive study of possible frequency combinations to achieve similar effects. We will compare PFM with actual frequency modulation and assess its effectiveness at other body sites, like the fingertips. We will explore the possibility of using beat perception [28] to lower the frequencies below 20 Hz (for low speeds and coarse textures) while keeping the amplitude perceptually strong. We will also evaluate the use of more than two single-frequency components to further broaden the PFM's operating frequency range.

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