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Presenting surface features using a haptic ring: A psychophysical study on relocating vibrotactile feedback

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Abstract—In the context of wearable technologies, it is often important for the fingers to be unconstrained so that they can be used to explore the environment. In this paper, we explored the feasibility of presenting vibrotactile cues that represented different textures to one of three locations on the hand and forearm using a wearable device. The first experiment indicated that vibrotactile signals of varying frequency rendered by the tactile display could be encoded by participants in terms of changes along a roughness-smoothness dimension. The differential thresholds measured for vibrotactile frequency were significantly higher on the wrist as compared to the fingerpad and the distal phalanx of the index finger. In two subsequent experiments vibrotactile signals were presented by a tactile ring worn on the distal phalanx and participants evaluated real textures explored by the fingerpad and virtual textures rendered by the ring. It was found that participants could compare and rank in terms of roughness two spatially distributed inputs with reasonable accuracy. In the context of the haptic ring being developed, these findings indicated that it is feasible to display information experienced at the fingertip on a more proximal location on the hand, thus freeing the fingers for other tasks.

Index Terms—Haptic interfaces, wearable haptics, perception, vibrotactile force feedback, haptic rendering, wearable devices, wearable interfaces

1 Introduction

Over the past 20 years, a number of haptic interfaces have been successfully developed with the aim of reproducing the sensations that a person experiences while touching an object [1]. These devices are able to provide a range of forces to the user, but most of them are neither portable nor wearable. Their mechanical bulk is typically incompatible with haptic feedback at multiple locations and they are often unable to provide cutaneous stimuli to the users' fingertips [2]. There is an increasing demand for novel displays that are wearable and can enhance a user's interactions with the environment. Such devices may be integrated into clothing or accessories in contact with the body, such as wristbands or pendants [3]. With wearable devices novel forms of communication, cooperation, and integration between humans and robots will be enabled.

Several devices have been developed that present tactile cues to the fingertips. Sarakoglou *et al.* described a wearable tactile display comprising a 4 x 4 array of tactors that moved perpendicular to the skin surface; the tactors were spring loaded and actuated remotely by dc motors through a flexible tendon transmission [4]. A compact fingertip-mounted device capable of stretching the skin to render shear forces was described by Gleeson *et al.* [5]. Pacchierotti *et al.* developed a 3-DoF device to provide cutaneous cues to the fingertips using a mobile platform that was designed to enhance the performance of robotic teleoperation systems [6]. In all these devices, it is not possible for users to easily switch between a virtual scenario and the real world, nor to change the tactile feeling of real objects by augmenting them with virtual textures.

Other research groups have placed wearable vibrotactile devices on different parts of the body and used them as a means of communication. For example, vibrotactile bracelets and belts have been developed to guide users in navigating in unfamiliar environments and directing people to target locations [7]. Vibrotactile vests worn on the torso have also shown promise in providing spatial cues to aid navigation [8] and assisting people with vestibular impairments in maintaining postural stability [9]. These body-based wearable systems have all been tested in mobile users with no constraints in terms of tethering.

When we explore an object haptically most of the sensations are experienced on the fingertips. A wearable device that mimics these sensations strongly constraints the types of interactions possible with the surrounding environment since the fingers are no longer unencumbered. For this reason, we have been interested in exploring the feasibility of relocating the haptic feedback typically experienced on the fingertips to more proximal sites on the body where devices are commonly worn. Rings are usually worn on the proximal phalanges of the fingers and wristbands and bracelets around the wrist, neither of which impedes movements of the fingers.

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(a) (b) (c)

Fig. 1. The vibrotactile device worn on (a) fingerpad, (b) proximal phalanx, and (c) wrist. To ensure user comfort and better contact between the voice coil actuator and the skin, the lower part of the housing had a slightly different curvature depending on the location of the device.

Pacchierotti *et al.* [10] developed a cutaneous device called the hRing that presented normal and shear forces on the dorsal surface of the proximal phalanx of the index finger. They found that placing the tactile display at this location avoided problems with occlusions in tracking the position of the hand and aided task performance. Other researchers have examined the potential of using wearable ring devices to deliver localized tactile feedback [11], for gesture recognition [12] and as a platform for text input into different devices [13], [14]. Wrist worn accessories such as watches have a long tradition in the wearable computing literature [15], [16], [17], [18]. Recent advances in miniaturization and diminishing costs of batteries, processors, sensors, and communication technologies are now enabling smartwatches to move from the specialist market to the mainstream [19]. In many of these applications it is proposed that the watch acts as a proxy interface between a user and a mobile device. For example, Pasquero *et al.* [20] introduced a haptic watch prototype, in which actuators on the base of the watch touching the skin provided eyes-free haptic communication with an adjacent mobile device.

Moving the haptic device from the fingerpad to the proximal phalanx or to the wrist allows users to perceive cutaneous cues without limiting the interaction with real objects, for example in a AR scenario. This leads to some issues that may impact how these devices are designed and used: *i)* human tactile acuity varies across the skin surface which may limit the ability of users to interpret different spatio-temporal patterns of stimulation; *ii)* relocating haptic cues away from the actual location where they are typically experienced may degrade the sense of realism associated with contact on the fingertips.

In the present work, we aimed at addressing these issues by conducting psychophysical experiments to characterize how participants perceived the same vibrations when presented on three different areas of the hand: the fingerpad, the dorsal side of the proximal phalanx, and the dorsal surface of the wrist (depicted in Fig. 1). We were also interested in determining how people perceptually encode variations in vibration frequency as varying roughness. Despite the large number of studies on the amplitude required to detect vibration as a function of the frequency of stimulation [21], [22], there have been relatively few studies of vibrotactile frequency discrimination. The frequency and amplitude of vibration are not perceptually orthogonal and so as the amplitude of vibration increases (at a constant frequency), the perceived frequency of the signal (i.e., pitch) also increases [23]. The Weber fraction (i.e., the differential threshold divided by the reference frequency expressed as a percentage) for vibrotactile frequency is not a constant and changes as a function of frequency. Estimates of the differential threshold vary considerably from 18% to 50% for frequencies ranging from 25-200 Hz [24], to 30% at 20 Hz and then decreasing with increasing frequency to 13% at 200 Hz [25]. In the latter study, the authors noted that there was no difference between the fingertip and the forearm in terms of vibrotactile frequency discrimination. In this paper, a wearable vibrotactile display whose main component is a small voice coil actuator was built to conduct the psychophysical experiments. Because of its small size, the display can easily be placed on different parts of the hand and the forearm.

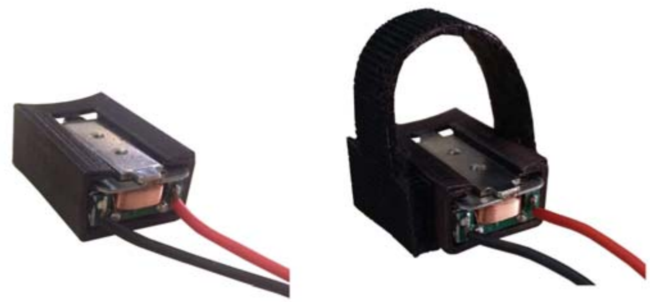
After conducting the first experiment we determined that the proximal phalanx was the most promising location in terms of performance and wearability. Two additional experiments were performed to evaluate whether the vibrotactile cues rendered by the vibrotactile device are of sufficient resolution that they can be matched to real textures explored by the fingertip, even though they are perceived on the proximal phalanx.

2 Device description

A wearable device was built in which tactile feedback is delivered to the skin through a voice coil actuator (Bone Conductor Transducer, Adafruit Industries, USA). The actuator is housed in a metallic case and, due to its lightweight ($9.6\,\mathrm{g}$) and small size ($14\,\mathrm{mm} \times 21.5\,\mathrm{mm} \times 7.9\,\mathrm{mm}$), is an excellent candidate for a wearable display.

A housing (3D printed) was fabricated to encase the actuator, as shown in Fig. 2. A small velcro strip is used to keep the actuator in constant contact with the user's skin, independently of the site on the body. A hole in the housing permits direct contact between the skin and the moving part of the actuator. With its simple design, a user can easily wear the tactile display and perceive different kinds of vibration on the fingerpad, the proximal phalanx of the finger, or the wrist.

The input signal to the voice coil actuator is produced by a computer sound card. The PortAudio cross-platform 'C'



(a) (b)

Fig. 2. The vibrotactile device, composed of a voice coil actuator embedded in 3D printed housing. (a) The design of the housing includes an opening corresponding to the moving platform, to ensure direct contact with the skin. (b) The housing is covered by velcro strips, which are used to attach the device to the fingerpad, proximal phalanx or wrist.

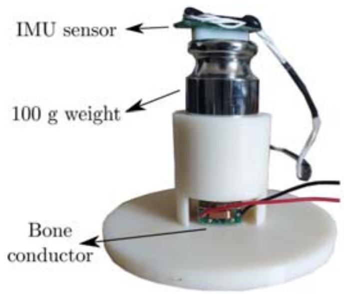


Fig. 3. The setup used to characterize the actuator.

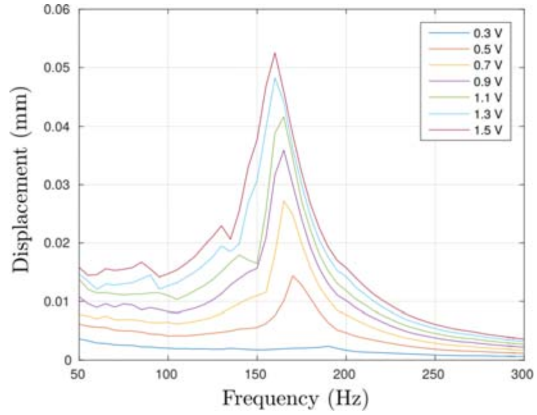


Fig. 4. Displacement of the actuator under load as a function of frequency and input voltage.

API for audio input and output [26] is used. Each stimulus presented to the user consists of a sinusoidal wave of arbitrary amplitude and frequency. Since the voice coil requires a higher current than that provided by the audio card output, the audio card signal is amplified by a filter-free Class-D audio power amplifier (TPA2016D2, Texas Instruments Inc., USA), programmed through a digital I2C interface by an Arduino Uno (Arduino, IT). The relationship between the required signal amplitude and the power amplifier's output was experimentally determined so as not to saturate the actuator; the laptop audio volume was set at 100%.

2.1 Device output characterization

To assess the relation between the input signal and the output of the vibrotactile device, the acceleration along the motion axis was measured. An IMU sensor LSM6DS3 (STMicroelectronics, CH) was attached to a $100\,\mathrm{g}$ weight, which in turn was fixed on the mobile platform of the actuator. They were placed on a support which was rigidly attached to a flat surface, with the moving axis of the actuator parallel to gravity (see Fig. 3).

The laptop provided different sinusoidal input signals to the device, ranging from 50 to $300\,\mathrm{Hz}$ and from 0.3 to $1.5\,\mathrm{V}$ with a step size of $5\,\mathrm{Hz}$ and $0.2\,\mathrm{V}$, respectively. The accelerometer output was recorded through a Teensy 3.2 Development Board (PJRC). The data were then analyzed to estimate the average peak acceleration for each input signal.

Fig. 4 shows all the displacement peak values for each frequency, with different curves showing different applied voltages. Since we are dealing with simple sinusoidal signals, the amplitude of the displacement of the vibrating plate has been computed by dividing the amplitude of the acceleration by $(2\pi f)^2$, with f the frequency of the sinusoid. For the sake of clarity, data interpolation has been performed. The results showed that the haptic device could move up to $0.052\,\mathrm{mm}$ along the axis of motion of the actuator.

Fig. 4 shows that the displacement of the mobile platform of the actuator was almost constant at low frequencies and then increased until it reached a maximum at 160-$190\,\mathrm{Hz}$, and then decreased at higher frequencies. Apart from the first experiment, in which a broad range of frequencies was used to measure the differential thresholds, in subsequent studies frequencies involving large displacements (i.e. 160-$190\,\mathrm{Hz}$) were not used. The frequency at which the displacement peak occurs will, however, change with different loads.

3 Experimental Evaluation

We carried out three experiments: *i)* to characterize how the perceived frequency of vibrotactile stimuli varies as a function of the location on which the signals are delivered, *ii)* to evaluate the ability to distinguish different real textures and virtual textures rendered as vibration signals, and *iii)* to investigate whether vibrotactile signals presented at one location can be mapped onto textures experienced at another site.

The first experiment evaluated how variations in vibration frequency were perceived by users when delivered at three different locations: the fingerpad (Fig. 1a), the dorsal surface of the proximal phalanx (Fig. 1b), and the dorsal side of the wrist (Fig. 1c). The objective was to determine whether the ability to perceive variations in vibrotactile frequency at the three sites was similar enough that the locations could be used interchangeably to present textural cues.

The second experiment was focused on evaluating the ability of users to discern the roughness of different textures, using both real and virtual stimuli. Blindfolded participants were asked to sort five textures from the smoothest to the roughest. The real textures were machined copper blocks with defined spatial periods and the virtual textures were vibrotactile signals generated to represent a similar range of stimuli.

In the third experiment participants were asked to map the tactile signals delivered by the ring to the physical surfaces. Participants had to match a virtual stimulus to one of the copper blocks.

3.1 Experiment 1: Perception of vibration frequency at three locations on the hand

The first experiment focused on vibrotactile perception and was designed to measure the 'difference threshold' (sometimes called the 'difference limen', DL) for roughness, defined in terms of frequency. Previous research had shown that by changing the modulation frequency of a base signal, waveforms can be created that are perceived as varying in roughness [27]. The main goal of the present experiment was to determine the smallest change in vibration frequency that can be perceived on the proximal phalanx and the wrist so that these values can be used as a baseline for creating different virtual surfaces.

Participants: Eleven volunteers, seven males and four females, took part in the experiment. They were aged between 20 and 53 (mean 29) years. None of them reported any deficiencies in sensorimotor function and all of them were right-handed. The experiment was approved by the local ethics committee, and all participants signed informed consent forms. Only one participant had previous experience with vibrotactile displays.

Methods: The same experimental procedure was used for the fingerpad of the index finger, the dorsal surface of the proximal phalanx of the index finger, and the dorsal surface of the wrist.

At the beginning of the experiment, the correspondence between higher frequency vibrations and smoother textures was explained to participants. They were told that the roughness of a surface is defined by its spatial period at a given scanning velocity and it is perceived by human beings as the change of frequency detected by mechanoreceptors [28]. It was explained to them that they would feel two consecutive vibrations with the same amplitude but different frequency and that they would select which stimulus was perceived as being smoother (i.e. higher frequency). A familiarization period of two minutes was provided to participants to acquaint them with the experimental setup. Pink noise was delivered through noise-canceling headphones to eliminate any auditory cues from the tactile display. Participants were asked to assume a comfortable position with the right hand and to maintain that position throughout the experiment.

Psychophysical evaluation: The just-noticeable differences or JNDs were determined for four standard stimuli (SS: 70 Hz, 140 Hz, 210 Hz, and 280 Hz) at a fixed amplitude (1.5 V) on the three sites, giving a total of 12 conditions. The stimulus provided by the vibrotactile device was a vertical (normal direction with respect to each body site tested) sinusoidal vibration. The amplitude was set so as to provide a clearly perceptible vibration while avoiding audio amplifier saturation for any input signal.

For each location, the experiment was divided into four conditions, one for each of the four standard stimuli. The order of presentation of the stimuli was randomized. On each trial the first stimulus was presented for 1.2 s, followed by a 0.3 s pause, and then the second stimulus was delivered for 1.2 s. After each trial participants indicated which vibration stimulus was smoother by entering their responses (one for the first or two for the second) on a keyboard. If participants did not perceive a particular pair of stimuli clearly, they could ask the experimenter to repeat the trial up to a maximum of four times. Throughout the experiment, participants asked to repeat a trial once on about 10% of trials, twice on 5% of trials, and three times on less than 1% of trials. No one asked to repeat the trial four times.

In the first trial, the comparison stimulus (CS) was set at 20 Hz higher than the standard stimulus. Then, using the transformed up-down method [29] the difference between the frequency of the CS and SS became smaller after two correct responses and increased after one incorrect response. The step-size for varying the CS started from 8 Hz and decreased after each reversal by 2 Hz. The last step-size was 1 Hz. This method gives a threshold at the 70.7% level. Since each participant had to complete the experiment on three different locations, we chose the staircase method because it has the shortest time to completion [30].

With such an experimental procedure a participant might have to compare a SS and a CS that are actually the same. On these trials, the participant's responses were considered incorrect which forced the algorithm to continue presenting stimuli in the same direction (i.e. increasing or decreasing) without compromising the position of reversals and without introducing any artifacts. The ratio of the difference threshold (ΔI) to the reference stimulus (I) is referred to as the Weber fraction.

In Fig. 5a an entire experimental run is shown, where '+' represents the correct answer and 'o' an error. Each experimental condition (one SS) was run until five reversals were completed. The first reversal was not used to calculate the just-noticeable difference. About 45 minutes were required to complete the experiment.

Results and Discussion: The Weber fractions were calculated as the mean difference between the CS and SS at the four reversal points and then averaged across all participants. In Fig. 5b, the Weber fractions for the four standard stimuli are shown for the three sites tested.

As shown in blue, on the fingerpad the data for the 210 Hz and 280 Hz stimuli are consistent across participants and the Weber fractions are quite similar. Performance is much more variable at 70 Hz and 140 Hz, where the data are not closely clustered around the mean. The mean Weber fraction for the fingerpad is 7.57%, varying from 4.91% to 11.04%. The results obtained on the proximal phalanx are consistent across participants. The mean Weber fraction is 5.97%, varying from 5.16% to 6.65%. In contrast when the display was worn on the wrist, the thresholds were higher than those measured on both the fingerpad and dorsal surface of the finger, with a mean Weber fraction of 13.07%, varying from 10.31% to 16.75%.

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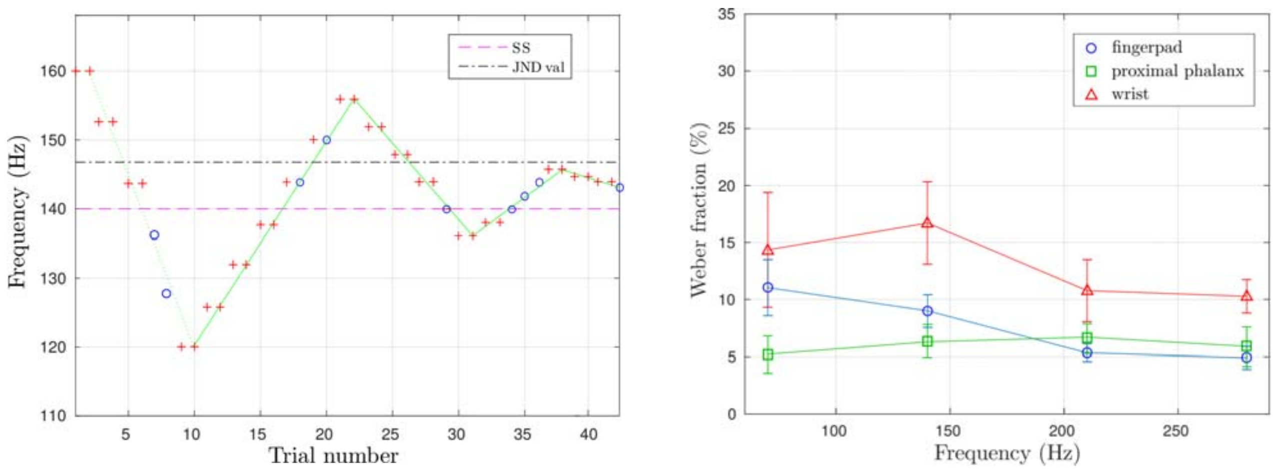

(a) SS = 140 Hz; A = 1.5 V

(b) Weber fractions

Fig. 5. Psychophysical evaluation:(a) an entire experimental run, where + and o represent the correct and wrong answer, respectively; (b) Weber fractions and standard errors of the means (SEM) for four different input signal frequencies (70, 140, 210, 280 Hz) are shown at the same signal amplitude (1.5 V).

A two-way repeated measures ANOVA was performed on these data with frequency and location as within-subjects factors. The original data were normally distributed with one exception, according to the Shapiro-Wilk normality test. It was assumed that the violation was not sufficient to warrant data transformation, particularly as all other residuals were normally distributed. The data passed the Mauchly's test of sphericity. The ANOVA revealed that there was a statistically significant difference between the locations ($F(2,20) = 11.012$, $p = 0.001$), but no significant effect of frequency. The interaction between location and frequency was not significant. Post hoc analysis with Bonferroni adjustments revealed a statistically significant difference between the wrist and the other two locations tested (fingerpad vs wrist, $p = 0.023$; proximal phalanx vs wrist, $p = 0.013$).

The difference in sensitivity between the wrist and the fingerpad is not unexpected in that it has previously been shown that the Weber fraction for frequency discrimination is consistently lower on the fingertip as compared to the forearm for frequencies between 20-200 Hz [25]. These differences can, in part, be attributed to variations in the sensory receptors and afferent fiber types supplying these two skin areas. In hairy skin, the detection of low vibrotactile frequencies appears to be based on sensory afferent fibers associated with hair follicles, whereas in glabrous skin the input arises from rapidly adapting fibers associated with Meissner corpuscles [21].

The variations in thresholds measured at the three locations may also reflect differences in the stiffness of the tissue underlying the tactile display. On the proximal phalanx the actuator was positioned directly over the bone with very little intervening soft tissue which may have facilitated transmission of the vibrotactile signal. In contrast, the pulp on the fingerpad is stiffer than the skin on the dorsal surface of the hand. It has been shown that for the same vibrotactile input the frequency and amplitude of vibration measured on the skin varies at different locations on the body. The frequency is higher and the amplitude is lower on the glabrous skin on the palm as compared to the hairy skin on the forearm [31].

In the present experiment, the thresholds measured at higher frequencies on the fingerpad are very promising in terms of indicating that the area is very sensitive to changes in frequency in addition to displacement. At lower frequencies (70-140 Hz) the proximal phalanx is more sensitive than the fingerpad to changes in vibrotactile frequency as shown by the smaller Weber fraction (5% vs 11%). These results certainly suggest that more proximal regions of the fingers have the sensory capabilities required to represent textural properties and so a ring is a feasible option for a wearable tactile display. Such a device still allows the user to interact freely with the environment since the fingers are unimpeded.

At all three sites most of the participants indicated that it was difficult to classify low-frequency vibrations. They reported that their perception actually changed when the frequency of the vibrotactile signal was below a certain threshold. Indeed, they declared that although they were able to perceive a difference between the stimuli, they could not determine which was 'smoother' or 'rougher'. They reported that the vibrations appeared to be of different amplitudes. This may reflect the interaction of vibrotactile amplitude and frequency noted previously. It is interesting to note that the Weber fractions measured in this experiment are lower than most of those reported for vibrotactile frequency discrimination [24] [25], which may reflect the instructions given to participants. They were told to focus on the relative smoothness and roughness of the signals rather than their frequency. Low Weber fractions of around 3% have, however, been reported for vibrotactile frequency discrimination using trains of short mechanical pulses varying in frequency instead of sinusoids [32].

The proximal phalanx has proven to be the most promising site among the three evaluated. For this reason, the following experiments were conducted only with the ring tactile display.

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3.2 Experiment 2: Ranking the perceived roughness of real and virtual textures.

Participants: Eleven volunteers, six males and five females, took part in the experiment. They were aged between 25 and 42 (mean 32) years. None of them reported any deficiencies in sensorimotor function and all of them were right-handed. The experiment was approved by the local ethics committee and all subjects signed informed consent forms. Three participants had previous experience with vibrotactile displays.

Methods: Participants performed the rank ordering experiment twice: with real textures and with virtual ones, rendered using the ring tactile device. During the first part of the experiment involving real textures participants were blindfolded. During the second part with virtual textures they wore noise-canceling headphones with pink noise playing to avoid any auditory cues. Participants were asked to assume a comfortable position with the right hand and to maintain that position throughout the experiment.

Experimental setup: To cover a range of spatial frequencies, five textures of varying roughness were chosen. The textures were created by machining the surfaces of five copper blocks ($25.5 \times 28.5\,\mathrm{mm}$, $6.0\,\mathrm{mm}$ thick) with a pattern of truncated pyramids using a wire EDM (Charmilles Technologies Robofil 1020SI Wire EDM). The truncated pyramids were a constant height of 500 μm, and spaced at periods of 800 μm, 1000 μm, 2000 μm, 2500 μm, and 3000 μm to convey smooth and coarse textures, as illustrated in Fig. 6. Measurements were made of the height and spatial periods of these stimuli using a surface roughness tester (Mitutoyo SurfTest SV-3000S4) and these indicated that the surface profiles had been machined accurately. The RMS surface roughness ranged from 165 μm (800 μm spatial period) to 216 μm (3000 μm spatial period).

To generate the virtual textures five different sinusoidal signals were produced that corresponded to the vibration patterns experienced when touching real textured surfaces. First, we characterized the velocity of the finger while it moved across the copper blocks. The index finger of three participants was attached to the handle of an Omega.3 haptic interface (Force Dimension, CH) and participants were asked to freely explore one of the blocks. The velocities of the movements in the two directions of the contact plane were measured. Results showed that the speed ranged from $0-0.3\,\mathrm{m/s}$ with a median of about $0.2\,\mathrm{m/s}$. An average speed of $0.2\,\mathrm{m/s}$ was therefore used. We then calculated the frequency of the sinusoidal wave representing each virtual texture as the ratio of the average speed to the spatial period of each block. The resulting frequencies were: $250\,\mathrm{Hz}$, $200\,\mathrm{Hz}$, $100\,\mathrm{Hz}$, $80\,\mathrm{Hz}$, and $66\,\mathrm{Hz}$ (see Table 1).

To select the magnitude values we took into account the results described in Sections 2.1 and 3.1 and the literature on the relation between perceived amplitude and frequency of vibrotactile signals [28] [33]. The results from the first experiment suggested that the perceived intensity of low frequency stimuli is smaller than that of higher frequency signals of the same amplitude. For this reason, an amplitude of $1.5\,\mathrm{V}$ was set for these signals ($66\,\mathrm{Hz}$, $80\,\mathrm{Hz}$, $100\,\mathrm{Hz}$). With

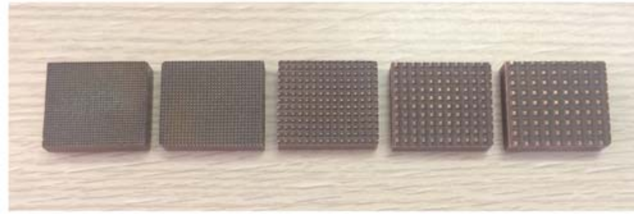

Fig. 6. The five copper blocks used as reference textures. The surfaces were machined with a pattern of truncated pyramids with a constant height of 0.5 mm and spaced at periods of (from left to right) to 800 μm, 1000 μm, 2000 μm, 2500 μm, and 3000 μm.

TABLE 1
Vibration stimuli

Position	Spatial period [μm]	Amplitude [V]	Frequency [Hz]
1	800	1.0	250
2	1000	1.0	200
3	2000	1.5	100
4	2500	1.5	80
5	3000	1.5	66

the present device a value of $1.5\,\mathrm{V}$ is about the maximum that can be used before saturating the voice coil. A value of $1.0\,\mathrm{V}$ was selected for the high frequency signals ($200\,\mathrm{Hz}$, $250\,\mathrm{Hz}$). It was anticipated that this adjustment meant that the different vibration signals were perceptually equivalent in terms of intensity.

Ranking procedure: The first part of this experiment evaluated whether participants could distinguish the real textured surfaces in terms of their perceived roughness. Blindfolded participants were asked to sort the five copper blocks, arranged in a random order on the bench, from smoothest to roughest. They were given two minutes to complete the task. The experimenter then entered the sequence on a keyboard.

After completing the first part of the experiment, participants then ranked the five virtual textures simulated by the tactile device that were presented in a random order. The display was attached to the proximal phalanx of the right index finger. The duration of each stimulus was $1\,\mathrm{s}$ with an interstimulus interval of $20\,\mathrm{ms}$, so as to avoid the temporal enhancement of the second stimulus occurring when two stimuli are separated by $100-500\,\mathrm{ms}$ [34].

Participants ordered the stimuli and were allowed to make adjustments to the sequence each time the new sequence was presented. They would indicate which stimuli should be switched and the new sequence was then presented. The experiment continued until participants indicated their final choice had been made or the maximum available time (five minutes) had elapsed.

Results and Discussion: To evaluate the performance of participants an error metric based on the position of each copper block in the participant's final sequence and the ranked position as defined in Table 1 was calculated. For each element of the participant's sequence we found the corresponding rank order of the physical or virtual texture and calculated the difference between the two position indices, defined as a *shift value*. For a vector composed of 5 elements, this value ranges from 0 to 4, according to the

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shift in position of the element.

In the following example

Submitted sequence = [1 3 4 2 5]

0 ↓ 1 ↘

Correct sequence = [1 2 3 4 5]

the five position shifts are
$|1-1| = 0; |2-3| = 1; |3-4| = 1; |4-2| = 2; |5-5| = 0$
.

Real textures: The results showed that 6 out of 11 participants ranked the roughness of the copper blocks in the same order as the physical measurements and so made no errors. For the remaining five participants, 11 textures were not in the correct positions, three involving a shift of two positions and 8 involving a shift of one position. In Fig. 7a the distribution of the *shift values* as a function of frequency is shown.

Virtual textures: The results with virtual textures indicated that 8 out of 11 participants made no errors. For the remaining three participants, 6 errors have been made, two involving a shift of two positions and four involving a shift of one position. The distribution of the *shift values* as a function of frequency is shown in Fig. 7b.

The superior performance of participants in ranking the virtual textures as compared to real textures (73% vs 55% of participants had perfect scores, respectively) may be due to the order of presentation of the two sets of stimuli. All participants were tested with the real textures first. However, given the differences between the two sets of stimuli and the single trial it seems unlikely that there would be a significant learning effect associated with this initial condition. Most of the errors with the real textures occurred for textures with larger spatial periods, that is those with coarser features (see Fig. 7). The perception of such textures is known to be spatially mediated through the activation of slowly adapting mechanoreceptors that densely innervate the fingertip [35]. Presumably the signals arising from these spatial patterns of activation as the finger scanned the surface were not highly discriminable for the set of textures presented. The virtual textures presented on the proximal phalanx of the index finger may have elicited more widespread activation of cutaneous mechanoreceptors resulting in more readily identifiable textural features.

3.3 Experiment 3: Matching real and virtual textures

The final experiment was a matching test involving the real and virtual textures. The objective was to evaluate whether vibrotactile signals representing virtual textures displayed on the proximal phalanx of the index finger could be mapped onto real textures explored more distally with the fingerpad.

From the pilot experiment described in Section 3.2, in which the velocity of the finger as it explored real textures was used to model the five virtual textures, it was evident that the speed can change so quickly that the participant does not perceive the resulting variations in frequency on the skin. Since the surface features of the copper blocks are small and exploration speed is highly variable, it was difficult to perceive clear differences in terms of the frequency of the sinusoidal wave. For this reason, we decided to maintain the frequency constant during each stimulus presentation.

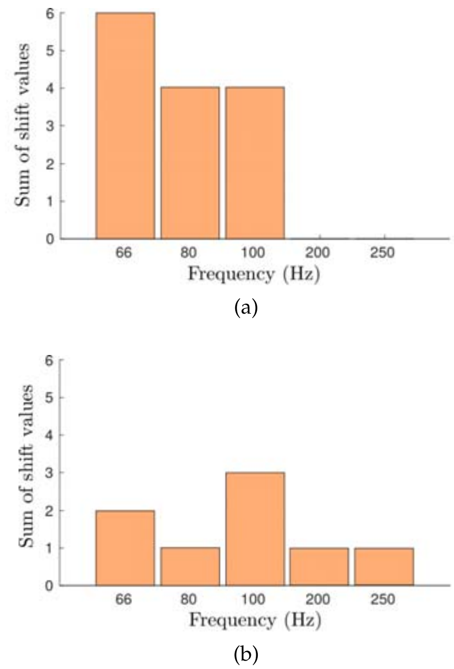

Fig. 7. Sum of the shift values for each stimulus defined in terms of frequency, for the experiment with (a) real and (b) virtual textures.

Participants: The same eleven volunteers from the second experiment also participated in the third experiment. The two experiments were conducted on the same day.

Methods: Participants were blindfolded and wore noise-canceling headphones with pink noise playing to avoid both visual and auditory cues regarding the stimuli (Fig. 8a). They were asked to assume a comfortable position and wore the tactile display on the right index finger, while they explored the copper blocks with the left index finger (see Fig. 8b). They were instructed to select the block that was most similar in texture to the vibrotactile stimulus being presented by the tactile device.

Matching procedure: Prior to the experiment, the five stimuli generated by the tactile display were presented to participants from smoothest to roughest. Then, one of the five virtual textures was randomly selected and presented four times to the participant. The duration of each presentation was $1\,\mathrm{s}$ followed by an interstimulus interval of $20\,\mathrm{ms}$. The virtual texture was repeated so as to mimic the conditions under which participants explored real textures which was by moving the finger across the surface repeatedly. Participants could ask for the stimulus to be repeated up to three times before they selected the matching real texture from the copper blocks.

The experiment was composed of 15 matching trials randomly ordered, with each of the five virtual stimuli being presented three times. For each stimulus, the participant

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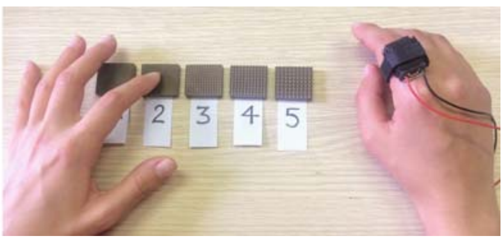
(a)



(b)

Fig. 8. The experimental setup for the matching experiment.

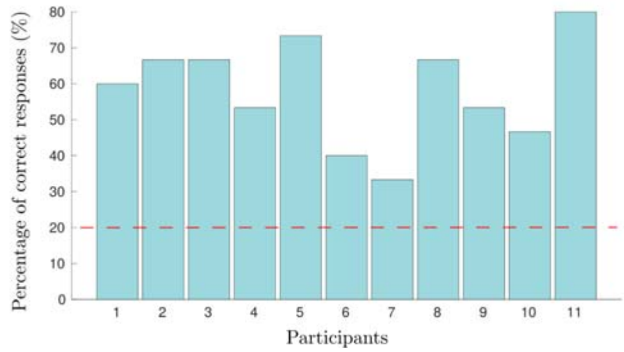


Fig. 9. Percentage of correct answers during the matching experiment between real and virtual textures, for each participant. The dashed line represents chance performance.

TABLE 2
Confusion matrix with scores out of the total of the 33 trials presented for each stimulus.

Participants' responses (Hz) \ Provided stimulus (Hz)	66	80	100	200	250
66	24	7	3	0	1
80	6	15	11	2	0
100	2	10	13	8	1
200	1	1	6	19	6
250	0	0	0	4	25

chose the corresponding real texture from the array and the experimenter recorded the response on a keyboard.

Results and Discussion: The group mean score expressed as a percentage was 58.2% correct, with the individual scores ranging from 33.3% to 80.0%. In this experiment, chance level performance would be 20% correct. Fig. 9 shows the individual data from participants.

Most errors consisted of a shift of only one position, that is selecting a real stimulus that was either slightly rougher or smoother than the virtual stimulus. Thus, we computed a *weighted error* based on the magnitude of the *shift values* defined in Section 3.2. The weighted error metric used in this study ranges from 0 to 48, with a score of 0 indicating the real and virtual textures with similar softness/roughness were perfectly matched. The maximum error score is 48, corresponding to the sum of the highest *shift values* (16) multiplied by the number of times (3) each stimulus is presented during the experiment. The mean weighted error over all participants is 7.55 (i.e., 15.73% of 48).

The confusion matrix of the participants' responses shown in Table 2 indicates that the lowest and highest frequency stimuli were the easiest to identify and most errors involved a single mislocation. Summarizing the results of the matching experiment, we can state that although the number of errors is relatively high (41.8%), most of the errors reflected a shift of only one location (see Table 2), which suggests that the tactile device can display cues that are perceptually mapped onto varying levels of roughness.

4 Conclusions and Future Work

In this paper, a series of psychophysical experiments was conducted to evaluate how variations in vibrotactile frequency are perceived at three locations on the arm. A lightweight wearable display has been developed that presents vibrotactile stimulation to a user's skin. The display was first characterized in terms of its displacement as a function of the frequency and amplitude of a sinusoidal input.

In the first experiment it was found that the differential thresholds for vibrotactile frequency were significantly higher on the wrist as compared to the proximal phalanx and fingerpad, and overall the lowest thresholds were measured on the proximal phalanx of the index finger. In contrast to the marked differences in detection thresholds for vibrotactile stimuli at the three sites [21], these results show that vibrotactile frequency discrimination is remarkably similar in hairy and glabrous skin, as has been noted previously [25]. However, the Weber fractions reported in the latter study [25] were twice those measured in the present experiment. The findings from the first experiment also indicated that the wearable tactile display was able to render vibrotactile signals of varying frequency that participants could encode in terms of changes along a roughness-smoothness dimension.

In the subsequent experiments real textures created by machining the surface of copper blocks and virtual textures presented using the tactile display mounted on the dorsal surface of the index finger were used to evaluate texture perception. It was found that participants could rank the virtual textures in terms of their perceived roughness with 73% of participants making no errors. Their performance on this task was superior to that with real textures, particularly for the lower frequency (rougher) stimuli. When scanning a textured surface with the fingers tactile information is encoded both spatially and temporally. Temporal cues are determined by the velocity of the finger movements along the scanning direction. Such cues are crucial for perceiving the roughness of finely textured patterns, but can also be important when scanning rougher surfaces [36]. In the second experiment, the copper surfaces were scanned at a self-selected velocity, which may not have been optimal for these particular textures. The differences in discriminability of the real and virtual textures may reflect the more intense nature of the vibrotactile stimulus as compared to the vibrations elicited by scanning the finger across the copper surface. Higher amplitude signals would travel further across the skin on the hand and arm resulting in more extensive activation of mechanoreceptors [31].

In the final experiment participants were able to match real textures explored by scanning the surface with the index finger to virtual textures experienced as a vibrotactile pattern on the dorsal surface of the index finger. Although the overall matching performance was only 58% correct, when matching accuracy is considered as being within one stimulus location of the correct response, performance is now 93% correct. These findings suggest that it is possible for participants to compare and rank in terms of roughness two spatially distributed inputs with reasonable accuracy. In the context of the haptic ring being developed, this means that it is feasible to display information experienced at the fingertip on a more proximal location on the hand, thus freeing the fingers for other tasks. The vibrotactile information presented by a ring does not necessarily capture the sensations associated with exploring a real surface on the fingertip but provides sufficient information for a user to distinguish between different surface textures.

In these experiments, participants were asked to judge the roughness of a virtual texture that was defined in terms of the frequency of a vibrotactile signal and compare it to the roughness of a hard physical surface that was manually explored. Although roughness is a dimension that emerges in descriptions of varying vibrotactile waveforms delivered to the skin and can be used to distinguish between such signals [27], [37], it is not necessarily the case that this roughness is perceptually equivalent to the roughness experienced when the fingers move across an abrasive surface. The present experiments have not examined the degree of realism associated with the virtual signals, but have demonstrated the potential for mapping between these two perceptual entities. This paper was focused on demonstrating the feasibility of presenting tactile cues at a location different from the interaction site. In this context, a compromise between wearability of the haptic device and realism of the tactile cues is required.

Future work will involve enhancing the performance of the tactile device by using more complex input signals to display different textures. The present experiments involved coarse textural features as defined in terms of the spatial periods of the machined copper blocks. It will be important to characterize the ability of the haptic ring to render fine textural details. Finally, one of the objectives in developing the haptic ring is to incorporate it into an integrated system that can be used in augmented and virtual reality applications.

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