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Vibrotactile thresholds on the wrist for vibrations normal to the skin

Quentin Consigny, Nathan Ouvrai, Arthur Paté, Claudia Fritz and Jean-Loïc Le Carrou

***Abstract*—In order to facilitate the development of wrist-worn vibrotactile devices, detailed knowledge about how vibrations are perceived by the users is needed. In particular, perceptual thresholds in amplitude are really important. Thresholds have been measured in the literature for other areas of the body, but given the variability reported between areas (shape of the threshold curve, position of maximum sensitivity), thresholds on the wrist can not be inferred from previous measurements and must be measured. The amplitude thresholds for vibrations normal to the skin surface were evaluated on 28 participants, with a three interval forced choice method. They were measured for 7 frequencies that are classical in the literature about vibrotactile perception (25, 40, 80, 160, 250, 320, and 640 Hz). The classical U-shape of the amplitude-threshold curve is observed, with a maximum sensitivity at around 160 Hz, which differs from other body areas, but confirms recent results obtained for vibrations parallel to the skin surface of the same body area. The sensitivity thresholds of vibrotactile signals appear to be in the micrometer range.**

I. INTRODUCTION

The number of vibrotactile devices worn on the wrist has increased in recent years. These devices can be designed for research activities [1]–[4] or developed for a "general public" use (connected watch or haptic metronome[1] for example). Wrist-mounted vibrotactile devices have three advantages: (1) a good sensitivity due to a relatively high density of mechanoreceptors (there are 10 times more receptors on the wrist than on the back) [5]; (2) a low bone conduction of sound [6] so that purely vibrotactile applications can be targeted, where the vibrotactile message can be broadcasted in noisy environments and accessible to hearing-impaired users and (3) a good accessibility, allowing to keep the hands free. The emergence of new vibrators (electro-dynamic transducers dedicated to vibrotactile applications) allows diversifying the offer and the capacities of these bracelets [7]. The miniaturization and democratization of the technologies used in the generation of vibrotactile signals (sound card, transducer, battery, etc.) facilitates the design of wrist-worn vibrotactile devices. In recent years, new technology industries have developed new applications based on the use of the sense of touch. Users report a real interest in this kind of technology. Vibrotactile wristbands could therefore continue to develop in the coming years.

For this, it is necessary to have a good knowledge of the users' feelings in order to design the vibrators and to anticipate the perception of the proposed vibrotactile signals. A first approach, classically used in psychophysics, is to analyze, both in amplitude and frequency, the user's sensitivity to vibrotactile signals. Detection of these signals is an essential parameter that is important to characterize, in particular through the identification of perceptual thresholds [8].

Nevertheless, the perception and detection of vibrotactile signals is dependent on the context of the experiment, such as the type of vibrator [9], [10], the force exerted on it [11]–[13], the shape in contact with the skin [14], [15] and the user themselves (hairiness [15], [16], age [17], temperature [18]). Naturally, the area of the body that is excited induces significant variations: this was measured on the finger [19]–[23], the arm [24], the back [24], the thigh [25], the skull [26] or the mouth [27]. For the wrist, detection thresholds were determined by exciting the skin parallel to its surface (the motion of the vibrator is along the skin, mostly using shear forces) [28]. However, some vibrotactile bracelets (especially those using voice coils), deform the skin in the direction normal to this surface. Therefore, thresholds measurements with vibrations normal to the skin using such devices are needed and would complete the work previously done.

In this article, amplitude thresholds for vibrotactile signals were measured with an electrodynamic transducer, placed on the internal face of the wrist. In parallel, a vibratory characterization of the vibrators was carried out, with the aim of identifying the frequency response, sensitivity and distortion behavior of the vibrators. After a description of the method and the experimental protocol (Section II), the thresholds of vibrotactile perception are presented (Section III) and discussed (Section IV) before concluding (Section V).

II. METHOD

A. Material

The vibrotactile device used in this work is made of an electrodynamic vibrator[2] maintained in contact on the volar wrist[3] by a watchband[4] which can be adjusted. This model is powerful enough to generate easily perceptible signals while not exceeding the size of a watch (a size that is accepted by a large part of the population). The fixed part of this vibrator is inserted in a wooden plate of 5 mm thickness. The mobile part is made of a crown of a few mm^2 on which a

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[1] Pulse made by Soundbrenner.

[2] DAEX19CT made by Dayton Audio (4Ω and 5W).

[3] Internal face of the wrist.

[4] Silicone watchband with magnetic closure by Tasikar.

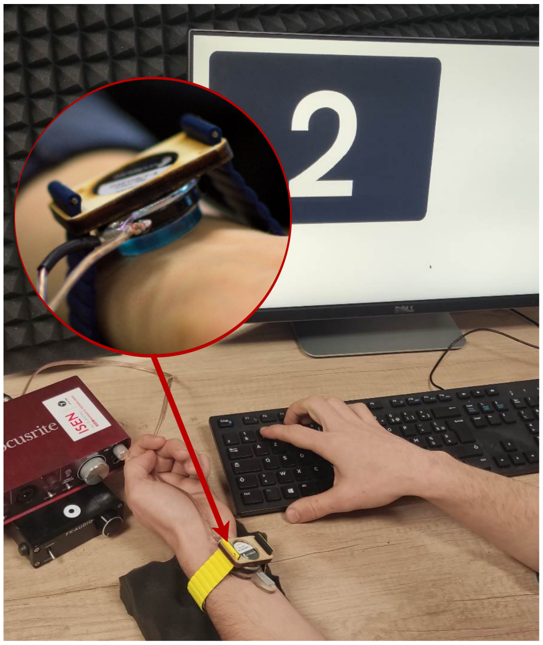

Fig. 1. Right-handed participant during the threshold measurement experiment. The vibrator is tightened by the wristband on the left volar wrist (corresponding to non preferred hand), the latter being placed on a foam limiting the transmission of vibrations. The participant uses their right hand to respond and identify the interval containing the stimulus.

Plexiglas disk (3 cm diameter, 3 mm thickness) is glued to facilitate the perception of vibrations [29], [30]. Studies on vibrotactile thresholds on the finger show that a decrease of the area of skin in contact with the vibrator lowers the perceptual thresholds and their evolution with frequency. For areas larger than a few tenths of a cm^2, the effect dissipates. This plate ($\approx$ 7 cm^2) thus makes it possible to get rid of this effect. The shape of the contactor (the Plexiglas disk) influences the perception threshold values [14]. The thickness of the disc prevents it from deforming under pressure. Thus, the shape of the contactor area is fixed, and is flat, neither concave, nor convex (see Figure 1). The notches of the watchband are a succession of 5mm wide magnets. The participants had to fit the bracelet by themselves so as the tightening felt comparable to the one used for a watch. Generally, once a participant found a comfortable tightness, adding a notch to the bracelet would make the vibrator lift off the skin while removing a notch generated too much tension on the bracelet so the magnets did not resist. With this tightening, participants exerted forces between 0.6 and 1.4 N (the mean value is 1 N, see Section VI), which is range of value already observed in a comparable study [13].

The bracelet had to be worn on the wrist of the non-preferred hand (i.e., left wrist for right-handed participant)

During the experiment, the participants were asked to keep the hand open and relaxed with the palm facing up. The participants' wrist rested on a piece of foam (see Figure 1). The participants wore earplugs[5] and ear muffs[6] in order not to hear the vibrator's noise (no participant reported having heard the stimuli). The earplugs and ear muffs each have an attenuation of 37 dB.

The vibrotactile signals were generated on a computer, then transmitted to a sound card[7], then amplified by an amplifier[8] to finally be sent to the vibrator. During the characterization and the threshold experiment, the output volume of the computer, the gains of the sound card and the amplifier were fixed. The maximum voltage at the terminals of the transducer was 3.3 V (peak to peak). This setup is visible in Figure 1.

B. Experimental characterization of the vibrator

In order to perform perceptual threshold measurements, it is important to characterize the vibrator while being used on the skin, in terms of (1) its harmonic distortion (check whether additional/unwanted frequencies are generated by the system: if not, it ensures that only the wanted frequency is tested) and (2) its voltage-displacement law in order to compensate for the frequency response of the vibrator.

For the first characterization, the device is fixed on the volar wrist of a subject (see Figure 2). This measurement is long and tedious, so it was only done with one participant. For each frequency, bursts of 25 periods of a sine wave are sent to the vibrator. The amplitude of the first burst corresponds to the amplitude of the smallest threshold identified in Section III (see table II), decreased by 15 dB. Each burst has an amplitude 1 dB higher than the previous one, until the maximum possible amplitude (of 3.3 Volts peak to peak) is reached. The velocity of the vibrator is measured with a laser vibrometer[9] and its controller[10] (see Figure 2). A Fourier transform is calculated on each burst. The harmonic distortion of the device is evaluated by computing the ratio between the sum of the amplitudes of the harmonics and the amplitude of the fundamental frequency [31]. This ratio is named THD (for Total Harmonic Distortion) and it is obtained as follows:

$$THD = 100 \times \frac{\sqrt{\sum\limits_{h=2}^{\infty} v_h^2}}{\sqrt{v_1^2}}, \tag{1}$$

where v_h is the RMS amplitude of the h-th harmonic. The THD is systematically measured for every generated burst. Table II-B shows the highest THD values measured. These values are low enough to consider that, for a sinusoidal voltage input, the movement of the transducer is sinusoidal with the same frequency [31].

The same data is used for the second characterization, as the velocity can be integrated to estimate the instantaneous position of the vibrator and then its RMS value. The RMS position calculated on a period can be considered constant over time (we consider that a low THD indicates a low distortion of the waveform, and that this distortion evolves little in time). In order to limit the integration errors, these instantaneous and

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[5] https://uk.rs-online.com/web/p/ear-plugs/1905877

[6] https://www.3m.co.uk/3M/en_GB/p/d/b00037368/

[7] Scarlett 2i2 by Focusrite, 24 bits, 44.1 kHz.

[8] FX1002A made by FX-AUDIO.

[9] OFV-353 made by Polytec.

[10] OFV-3001 made by Polytec.

Frequency (in Hz)	25	40	80	160	250	320	640
Highest THD (in %)	14.8	10.2	8.3	5.8	2.5	1.8	1

TABLE I
MAXIMUM MEASURED THD, AS A FUNCTION OF THE SIGNAL'S FUNDAMENTAL FREQUENCY.

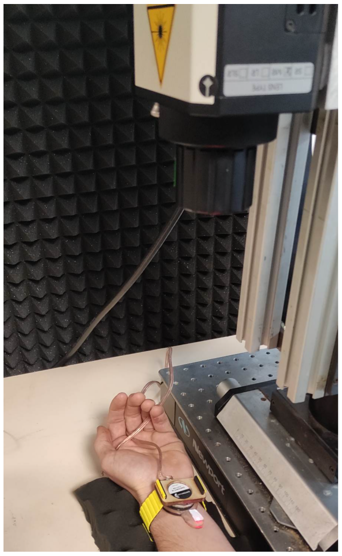

Fig. 2. Vibrotactile wristband in place on the wrist of a participant and pointed by the laser vibrometer.

RMS positions are calculated on each period, the measurement is reproduced for the 15 periods of the burst and an average is calculated over these 15 measurements. Thus, the voltage-displacement law can be estimated (see Figure 3). The thresholds can therefore be expressed in displacement in order to facilitate the comparison with other published results.

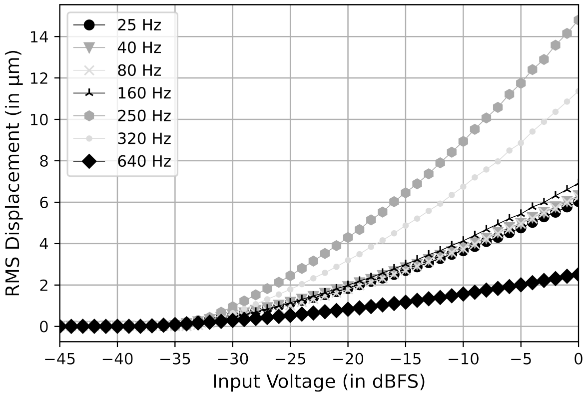

Fig. 3. Vibrator displacement as a function of frequency (different colors and markers) and input voltage (x-axis). The points represent averages over six measurements.

C. *Experimental protocol for the perceptual threshold*

The amplitude threshold is estimated for 7 frequencies classically used in the literature (25, 40, 80, 160, 250, 320 and 640 Hz) [14], [32] and covering most of the frequency range to which humans are sensitive via the vibrotactile modality [8], [30]. An "up-down" method associated with a "three interval forced choice" (3-IFC) procedure is used to determine the perceptual thresholds.

Figure 5 shows the threshold search method. For each frequency, a series of triads was presented to the participant (the order of these frequencies is randomized and balanced across participants). Each triad was composed of 3 one-second sequences (called intervals). Only one of those, chosen randomly, contained a stimulus. Between 2 intervals was a pause of one second. The participant could visualize on a screen (positioned in front of them) the current interval (see Figure 1). The workflow of the perceptual experiment is illustrated in Figure 4. At the end of the triad, the participant was asked to indicate in which interval they thought they perceived a stimulus. As long as the interval was correctly identified, a new triad at the same frequency was presented with a signal amplitude decreased by 3 dB. If not, the amplitude was increased by 3 dB and the process was repeated until the signal was identified 3 times consecutively. In a second step, the amplitudes were increased in 1 dB steps and 3 identifications in a row were systematically requested to consider the stimulus as perceived. This up-down pattern was repeated 3 times. The threshold is taken as the last amplitude. In order to reduce the duration of the experiment, the starting amplitude was set based on the results of a preliminary test (it was chosen between 3 and 26 dB below the maximum possible amplitude, depending on the frequency).

D. *Participants*

The experiment was performed with 28 participants. The participants ranged between 19 and 62 years, with a mean age of 28 years and a standard deviation of 11 years. Among the participants, 12 were women.

Participants were not compensated for their time. The study was approved by the research ethics committee of the University of Paris (IRB : 00012020-47).

III. RESULTS

A synthesis of the measured thresholds is shown in Figure 6 and Table II. The vibrotactile sensitivity seems to increase with frequency until it reaches a maximum at 160 Hz. Beyond this frequency, the sensitivity decreases constantly. Over these phases of decay and growth, the vibrotactile sensitivity seems to follow slopes of -6 and +9 dB per octave, respectively. The vibrotactile sensitivity curve is therefore U-shaped, centered at 160 Hz.

IV. DISCUSSION

It is a classical result of the literature that the vibrotactile sensitivity first increases in low frequencies, reaches a maximum, and then decreases in higher frequencies [8], [29], [30],

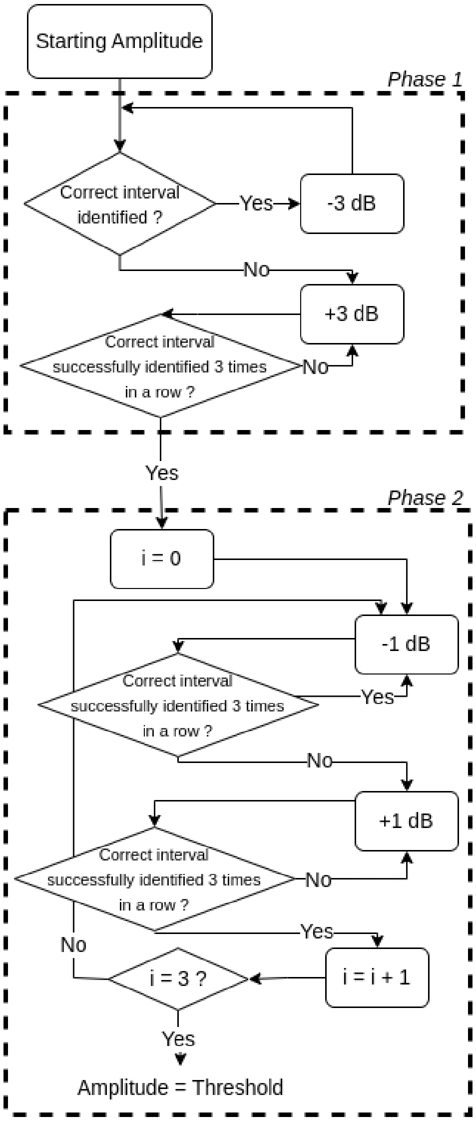

Fig. 4. Logigram of the threshold search method.

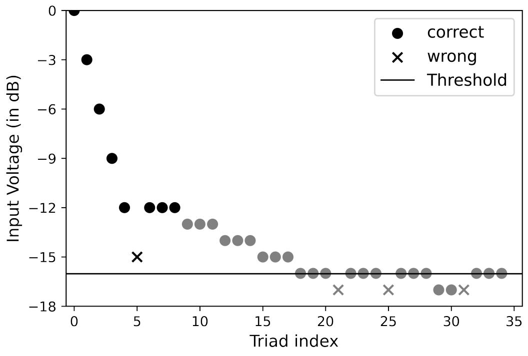

Fig. 5. Example of the threshold search method, for a given participant and frequency. Circles (resp. crosses) indicate correct (resp. wrong) answers. Black color indicates points separated by 3-dB steps, and gray color points separated by 1 dB steps.

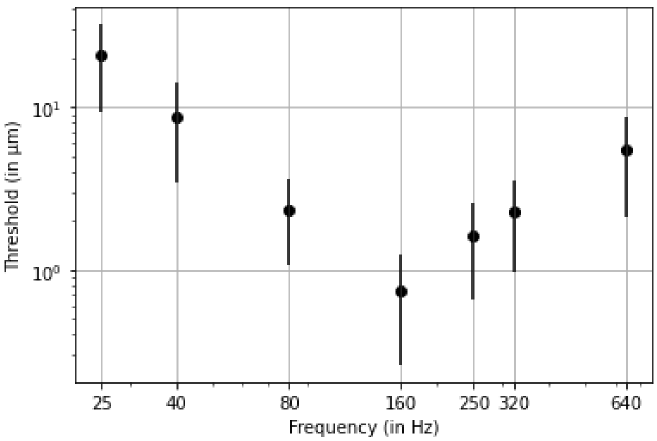

Fig. 6. Threshold of perception for the 7 frequencies. The average of the thresholds is represented by a dot, the vertical lines represent an interval of 2 standard deviations around this average.

Frequency (in Hz)	25	40	80	160	250	320	640
Threshold (in μm)	20.7	8.7	2.3	0.7	1.6	2.2	5.4

TABLE II
AMPLITUDE DETECTION THRESHOLD AS A FUNCTION OF FREQUENCY.

[33], [34]. The U-shape of this resulting curve (see Figure 6) is also classically observed [19], [34], [35], regardless of the stimulated body area. The maximum of sensitivity (minimum of the curve in Figure 6) is obtained here around 160 Hz, in agreement with thresholds obtained for vibrations parallel to the skin surface in this same body area [28]. It can therefore be assumed that the direction of application of the vibrations has little effect on the frequency of maximum sensitivity for this body area.

The inter-individual variability in the present experiment seems less important here than in other studies [28], [36], which may result from the difference in the direction of stimulation.

V. CONCLUSION

Perceptual thresholds in amplitude were estimated for vibrotactile signals applied normally to the internal side of the wrist. The trends observed on these perception thresholds (maximum sensitivity around 160 Hz, U-shaped curve) are in agreement with results already published, but measured with other vibrotactile devices and/or on a another body area.

The threshold search method used here is a classical method which allows a fine estimation of the threshold but leads to long experimental sessions. The estimation of a threshold for a frequency takes a few minutes. Some participants mentioned the monotony of the task. A fatigue phenomenon could have occurred and disturbed the results (the random order of the frequencies however probably limits its impact in the analysis). The use of a faster threshold search method (e.g. Audioscan [37]) may limit this problem and allow thresholds to be obtained for a greater number of frequencies.

One part of the protocol could be improved to increase the reliability of the results by measuring the vibrator displacement for each participant. This measurement would allow to directly consider the actual displacement of the vibrator instead of estimating it from measurements made on a single person.

Now that the detection thresholds on the volar wrist have been estimated, a next step could be to estimate the iso-sensitivity curves. It was already shown on other body areas that they tend to remain parallel to the amplitude perception threshold curve [19]. One can expect a similar trend for normal vibrations on the wrist, but this remains to be checked. Other psychophysical variables can also be studied in this context (JNDs in amplitude and frequency, for example). Variables that are fixed here (such as hand tightening and orientation, size of the surface in contact with the skin, type of transducers) may also be a focus of future work.

VI. APPENDIX : TIGHTENING FORCE ESTIMATION

Different methods of measuring the tightening force of the watchband were tested. The most classical one using a FSR sensor (Force Sensitive Resistor) was tested first. It is however impossible, in our case, to have a sufficient accuracy and fidelity of measurement. The forces involved in these tightening are too low to be measured repeatedly with a FSR sensor. Moreover, the introduction of this sensor between the vibrator and the skin modifies the coupling in an unknown way.

An original technique to indirectly estimate the force exerted by the tightening of the bracelet was designed. For this, the vibrator, without the watchband, is placed on the skin and different amounts of modeling clay are successively put on the vibrator to simulate different weights/tightening forces of the bracelet on the vibrator. The electrical impedance ($Z = U/I$ where U is the input voltage and I the current) of the vibrator is measured for each added mass, the resonance frequency and the modulus of impedance at this frequency are extracted. The Thiele-Small model suggests that the addition of mass modifies these physical quantities [38], [39].

A linear regression relating the value of the impedance modulus as a function of mass is determined (see dots and black line in Figure 7). From this regression, it is possible to estimate the force from the impedance modulus values. At the begining of the main experiment, the impedance modulus at resonance was measured, and the tightening estimated from linear regression (see gray squares in Figure 7). According to this method, the tightening of the watchband exerts a force on the vibrator of 1 N on average.

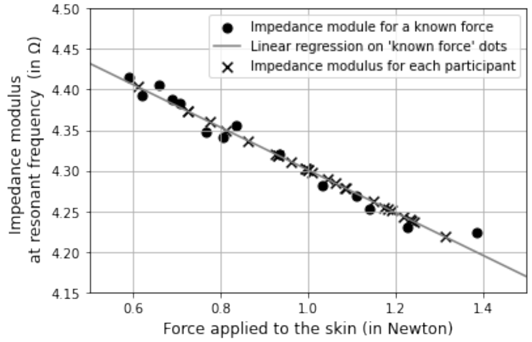

Fig. 7. Measured electrical impedance modulus at the resonance frequency as a function of the force exerted on the vibrator placed on the wrist.

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