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ELVAR ATLI ÆVARSSON, University of Iceland, Reykjavik, Iceland

THÓRHILDUR ÁSGEIRSDÓTTIR, University of Iceland, Reykjavik, Iceland

FINNUR PIND, University of Iceland, Reykjavik, Iceland

ÁRNI KRISTJÁNSSON, University of Iceland, Reykjavik, Iceland

RUNAR UNNTHORSSON, University of Iceland, Reykjavik, Iceland

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Vibrotactile Threshold Measurements at the Wrist Using Parallel Vibration Actuators

ELVAR ATLI ÆVARSSON, THÓRHILDUR ÁSGEIRSDÓTTIR, FINNUR PIND, ÁRNI KRISTJÁNSSON, and RUNAR UNNTHORSSON, University of Iceland

This article presents an investigation into the perceptual vibrotactile thresholds for a range of frequencies on both the inside and outside areas of the wrist when exciting the skin with parallel vibrations, realized using the L5 actuator made by Lofelt GmbH. The vibrotactile threshold of 30 participants was measured using a modified audiometry test for the frequency range of 25–1,000 Hz. The average threshold across the respective frequencies was then ultimately determined from acceleration minima. The results show that maximum sensitivity lies in the range of 100–275 Hz (peaking at 200 Hz) for the inside and 75–250 Hz (peaking at 125 Hz) for the outside of the wrist and that thresholds are overall higher for the hairy skin on the outside of the wrist than for the glabrous skin on the inside. The results also show that the vibrotactile thresholds varied highly between individuals. Hence, personalized threshold measurements at the actuator locations will be required to fine-tune a device for the user. This study is a part of an ongoing research and development project where the aim is to develop a tactile display device and a music encoding scheme with the purpose of augmenting the musical enjoyment of cochlear implant recipients. These results, along with results from planned follow-up experiments, will be used to determine the appropriate frequency range and to cast light on the dynamic range on offer for the tactile device.

CCS Concepts: • **Applied computing** → **Sound and music computing**;

Additional Key Words and Phrases: Cochlear implants, music enjoyment, vibrotactile detection thresholds, parallel vibration, psychophysical measurements

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1 INTRODUCTION

The **cochlear implant (CI)** is an important technological and biomedical achievement and is in many ways a highly successful neuronal assistive device. Such implants have restored hearing in hundreds of thousands of deaf and hard-of-hearing individuals over the past decades. Despite this success and the fact that both the technology and surgical techniques have vastly improved over the years, CIs are still far away from providing

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Authors' addresses: E. A. Ævarsson, University of Iceland, Skólbraut 3, 220, Hafnarfjörður, Iceland; email: elvaratli@hi.is; T. Ásgeirsdóttir, KTH Royal Institute of Technology, Lindstedtsvägen 3, 114 28, Stockholm, Sweden; email: thorhildurkristin@gmail.com; F. Pind, University of Iceland, Dunhaga 5, 107, Reykjavík, Iceland; email: finnurpind@hi.is; Á. Kristjánsson, University of Iceland, Sturlugötu 3, 102, Reykjavík, Iceland; email: ak@hi.is; R. Unnthorsson, University of Iceland, Dunhaga 5, 107, Reykjavík, Iceland; email: runson@hi.is.

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normal hearing. This is largely due to the fact that CI devices reduce the spectral information delivered to the brain by filtering the incoming acoustic signal down to 12–22 frequency bands, depending on the device. While CIs can work well in terms of one-on-one communication in quiet environments, complex signals such as speech-in-noise and music are very hard to convey. Hence, there are still areas of opportunity to further improve the music listening experiences of CI recipients.

The **ACUTE (ACoUstic and Tactile Engineering)** group at the University of Iceland seeks to enhance the musical experiences of CI recipients by circumventing limitations of the CI through supplementation of the auditory stimulation with tactile stimulation, i.e., complementing the CI with vibrotactile stimulation to the skin. A multi-channel vibrotactile display and an encoding scheme to map music to multiple channels of vibrotactile feedback is currently in development for this purpose. The long-term aim is to develop a device with multiple vibrotactile actuators that will convey musical elements with patterns of vibrations of different amplitudes and frequencies divided across the actuators in the display. The complementary tactile solution will benefit current CI users (over half a million) as well as future CI recipients, since a technological leap in CI technology is not expected anytime soon. It will benefit all those CI users, as reimplantation is only considered a last resort.

The research presented in this article is the first in a series of planned psychophysical experiments aimed at gaining fundamental knowledge for the design of a vibrotactile display for CI recipients. Clearly, since the device in development is intended to provide vibrotactile feedback at various frequencies, a thorough understanding of the vibrotactile thresholds of the skin across a wide range of frequencies, using the exact form of displacement provided by the actuator of choice (Lofelt L5, discussed in Section 2.1), is essential. Furthermore, as discussed in Section 1.2, the threshold values across different skin types must also be considered. We therefore designed an experiment to measure the vibrotactile thresholds of both the glabrous skin on the inside of the wrist and the hairy skin on the wrist's outside, with the aim of using the resulting information for frequency selection for the device and as input for amplitude compensation across frequencies in the encoding of the auditory signal.

1.1 The Cochlear Implant and Its Limitations

The cochlear implant provides a way of bypassing a dysfunctional inner ear. Auditory information is conveyed by directly triggering the auditory nerve via implanted electrodes, essentially compensating for the lost nerve impulses normally provided by the **inner hair cells (IHCs)**. CI processors follow a place coding strategy and mimic the interplay of the basilar membrane and the IHCs. High and low frequency acoustic signals activate the electrodes placed near the base and apex of the cochlea, respectively. This method enables the device to successfully convey the fundamental spectral elements of speech, such as the formants that characterize the vowels. However, current CI designs use 12–22 electrodes and the spectral resolution that they provide therefore cannot match the resolution provided by the IHCs, which number around 3,500 at birth. In addition, the relatively large distance between the electrodes and the auditory nerve results in a current spread inside the cochlea. This, in turn, results in unwanted overlap, with neighboring electrodes partially stimulating the same group of nerve fibers, decreasing the resolution of the auditory signalling of the CI [16]. The reduced spectral resolution experienced by CI users results in poor perception of spectral elements such as pitch, harmony, and timbre [5, 19, 24], which, among other things, greatly affects the perception of music.

1.2 Sensory Substitution

Sensory substitution presents a promising opportunity to add to the musical experiences of CI users with additional sensory stimulation to fill in the gaps of what is missing in their auditory perception. Sensory substitution builds on the idea that when loss occurs in one sense, it can be augmented through stimulation of another sensory modality [13, 15, 20]. Research suggests that sensory substitution offers a unique chance of rehabilitation for individuals with perceptual loss, as it has been shown that the brain has the capacity to employ information acquired through other sensory modalities to regain functionality in the defunct sensory organ [27].

1.3 Vibrotactile Sensitivity

With regard to music, it is important to note that music is not limited to the auditory modality, since air vibration also causes tactile stimulation, but mainly in lower frequency ranges. To create an effective tactile display solution, it is important to tailor the design to the specific sensory perception capabilities of the body. Tactile stimulation is perceived through the mechanoreceptors based in the outer two layers of the skin. For vibrotactile sensation, the most obvious receptors to take advantage of are the rapidly adapting Meissner corpuscles, which mainly detect low frequency vibration in the range of approx. 10–50 Hz, and the Pacinian corpuscles, which detect higher frequency vibrations at around 20–1,000 Hz [12, 25, 26]. The mechanoreceptors are more densely distributed in glabrous (hairless) skin than in hairy skin. Thus, the glabrous parts (fingertips, palms, soles, etc.) tend, on average, to be more sensitive to tactile stimulation through the skin than other parts of the body [23].

The vibrotactile sensitivity of the skin has been studied in the past [2, 6, 8]. A good example is the extensive research of R. T. Verillo [29, 30]. Using an experimental setup that produced vibration normal to the skin's surface, similar to that of a bone conduction transducer, he showed that the vibrotactile threshold curve for the glabrous skin on the fingertip is a U-shaped curve with maximum sensitivity at 250 Hz. A later study by Brisben et al. [4] suggests a lower tactile threshold as well as a maximum sensitivity shift towards lower frequencies (150–200 Hz) when the vibration is applied parallel to the skin's surface. Furthermore, Brisben et al. showed that contact force had no effect on the detection threshold.

The previous studies have used various forms of displacement in the vibratory devices and have shown that the type of stimulus (parallel/normal) affects the detection threshold. Our research group has until now extensively investigated vibrotactile perception [11, 12, 14], but this has been done using ERM motors as actuators, which rotate parallel to the skin and do not allow independent modulation of amplitude and frequency. With the experiment that we present here, our aim is to investigate the detection threshold using the exact form of tactile stimulus provided by the actuators of choice (L5 by Lofelt GmbH), with a flat surface area vibrating back-and-forth parallel to the skin. The wrist was chosen as the location for the stimulation, as measuring both the glabrous skin on the inside of the wrist and the hairy skin on the outside would give a good comparison between the detection thresholds of the two skin types.

Taking the previous findings and discussion above into account, one could form a rough hypothesis of the experimental outcome. First, the glabrous skin on the inside of the wrist should show more sensitivity to the vibrotactile stimuli than the hairy skin on the outside. Thus, a lower threshold is to be expected overall for the inside of wrist. Second, the thresholds for both sides should be a function of frequency, with minimum threshold (maximum sensitivity) at around 150–200 Hz and the threshold rising towards lower and higher frequencies.

2 METHOD

2.1 Apparatus

The vibrotactile stimulation in this experiment was provided by the Lofelt L5 actuator shown in Figure 1. The L5 is a voice-coil in a $17 \times 20.5 \times 6.2$ [mm] (W×D×H) plastic casing that responds to any audio signal. Putting the case flat up against the skin results in a back-and-forth vibration parallel to the skin's surface. The experiment was carried out using our in-lab audio-tactile research hardware system, specially designed for experimenting with multi-channel vibrotactile stimulation and feedback. However, for this particular experiment, only one channel was needed, because sensitivity was only measured on one side of the wrist at a time. The system is composed of an RME MADIface XT audio interface, two Ferrofisch A32 AD/DA converters, and a custom-made multi-channel 2 W amplifier.

2.2 Wristband Prototype

A wristband prototype was assembled to place the actuator securely and snugly against the skin. The wristband is made of stiff elastic material with Velcro strips sewn into the fabric for easy adjustment and fitting around



Fig. 1. The L5 actuator by Lofelt GmbH consists of a voice coil in plastic casing. A permanent magnet in the middle reacts to the magnetic field caused by the current flowing through the coil wire. Sine wave signals produce periodic upwards and downwards movements of the magnet (referring to the directions in the image). Placing the flat 17.0×20.5 mm case surface against the body results in vibration parallel to the skin [1].

the wrist. The L5 actuator is placed at the center of the elastic band and sticks via double-sided tape. 2 mm PETG copolyester plates (circular area, $d = 25$ mm) are glued to each side of the L5 to prevent the moving permanent magnet inside the L5 casing from scratching against the participants' skin or causing damage to the elastic material. Pin sockets were soldered to the L5 coil wires for signal input. Contact with the skin is ensured via the PETG plate.

2.3 Participant Demographics

A total of 30 participants (all naive, 18 female, ages 20–73 (mean = 33.47 years, median = 29.50 years, SD = 12.97), one left-handed) took part in the experiment after signing informed consent. Each participant received training on two practice trials before the actual measurements began.

2.4 Experimental Procedure

The experiments were performed in accordance with the requirements of the Icelandic Bioethics Committee and the Icelandic Data Protection Authority. Figure 2 shows the experimental setup. Participants sat on a chair across a table from the experimenter in a quiet room. All participants wore headphones that produced white noise to mask the audible tones from the L5 voice-coil actuator during the experiment. Participants wore the wristband on their dominant hand with their arm resting on sponges to neutralize the table surface and for comfort.

The absolute vibrotactile detection threshold was measured using a modified version of the MATLAB MLP toolbox by Grassi et al. [9]. The toolbox runs a standard audiometry test and calculates the threshold at each measured frequency via the **maximum likelihood procedure (MLP)** proposed by Green [10], an adaptive 2-alternative forced-choice procedure. Green's MLP determines the absolute auditory threshold by utilizing a large number of hypothesized psychometric functions (hypotheses), all with the same slope and false-alarm rate but with differing midpoints. Each tone is presented in an iterative manner and after each iteration, the response is used to calculate the likelihood of each hypothesis. The successive presentation level is then calculated based on the hypothesis with the maximum likelihood. At the end of the iteration process, the hypothesis with the maximum likelihood from the last iteration is used to calculate the absolute threshold.



Fig. 2. Experimental setup. A PC running the experiment connects to the audio-tactile hardware system via USB. A shielded audio cable carries the pure tone signals from the amplifier output (a) to the L5 input on the wristband prototype (b). Subjects wore headphones and were presented with white noise to mask the audible frequencies during the experiment.

For this experiment, the MLP toolbox was modified for the use of vibrotactile threshold measurements by shifting the measured frequency span from the standard audiometry frequencies of 125–8,000 Hz down to 25–1,000 Hz. Furthermore, the data was presented in dB FS (the amplitude level relative to full scale, i.e., relative to the maximum peak level of the digital system) rather than the standard audiometry presentation of dB HL (the amplitude level relative to average hearing level). Additionally, all pure tones were windowed with a Tukey window, $\alpha = 0.35$, to prevent perceptible transients. No gain (0 dB) was added to the audio signal by the hardware.

The vibrations were presented in 500 ms intervals in the following frequency step size breakdown (starting frequency : step size : end frequency); 25:25:275, 300:50:450, 500:100:1,000 [Hz], one frequency per trial. Each trial involved 20 iterations and 100 hypotheses to calculate the threshold (see discussion on Green’s maximum likelihood procedure above). The first two trials served as training, i.e., practice trials with the aim of familiarizing the participants with the process, to be repeated and the results overwritten later in the experiment.

Each participant was asked to indicate when the vibration was perceived, no matter how weak, either by verbal confirmation or by physical confirmation such as thumbs-up with their free hand. Participants were tested on both the inside and outside of the wrist (as shown in Figure 3). The order in which measurements of the two test conditions were performed was counterbalanced across subjects, with one half of the 30 participants total going through the procedure first on the wrist’s inside area and the other half first on the outside. Measurements of each condition lasted approximately 25 minutes. The participants were informed when they were halfway through each measurement and were offered a short break in between measurements. The experimental session lasted about an hour in total.

2.5 Mapping of Signal Amplitude to Vibration Acceleration Amplitude

The vibrotactile thresholds determined in the subjective experiment described above are recorded in terms of a relative signal level (measured in dB FS), i.e., the relative amplitude of the audio signal fed to the L5 actuator. It is

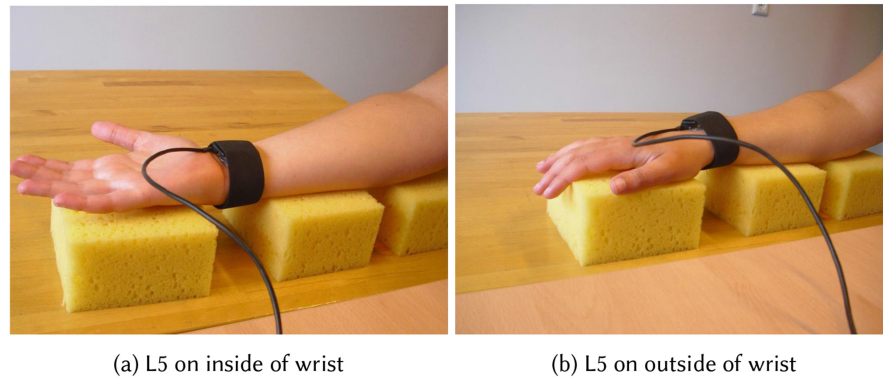


Fig. 3. Actuator placements during the experiment. Vibrotactile threshold was measured for both the glabrous skin on the inside of the wrist and hairy skin on outside of the wrist. Participants rested their forearm on sponges, with the L5 actuator on the top during the testing procedure.

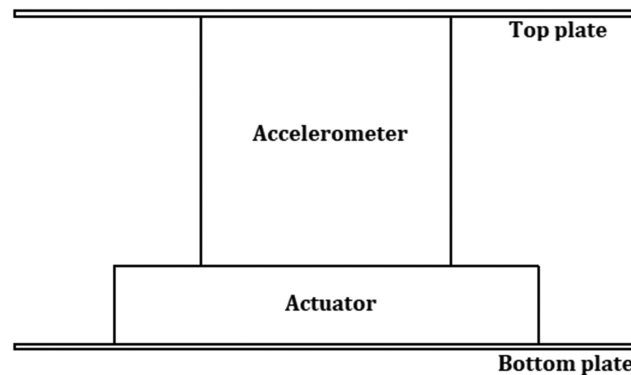


Fig. 4. Cross-section diagram of the acceleration measurement setup. The top plate is attached to the wristband and the bottom plate rests on the skin surface. A B&K 4507 accelerometer was fitted in between the wristband and the L5 actuator, and the wristband was then mounted on the hand in an analogous way as done in the subjective threshold measurements.

of interest to relate these signal levels to the vibration intensity (acceleration measured in g) at the skin. However, the L5 actuator has a non-flat frequency response, with the actuator datasheet showing a large resonant peak in acceleration at 65 Hz. Due to the non-flat frequency response, and due to the effect of mounting conditions, it is not possible to infer directly the vibration intensity at the skin from the recorded signal levels [18]. Instead, an acceleration measurement is necessary to relate these signal levels to the physical vibration intensity at the skin. This acceleration measurement is not a subjective measurement that is done for each participant, but rather a measurement of the actuator itself, a mapping from a signal level to an acceleration level. As a result, this measurement does not need to take place for each participant, as long as the mounting conditions are similar to those of the subjective test.

The acceleration measurement was carried out using a Bruel and Kjaer 4507 accelerometer that was fitted between the wristband and the actuator. The wristband—now including the accelerometer—was mounted on a hand of a single test subject, in an analogous fashion to what was done in the subjective threshold tests. Figure 4 shows the setup. The L5 actuator was fed the same pure tone signal as in the subjective threshold experiment, at

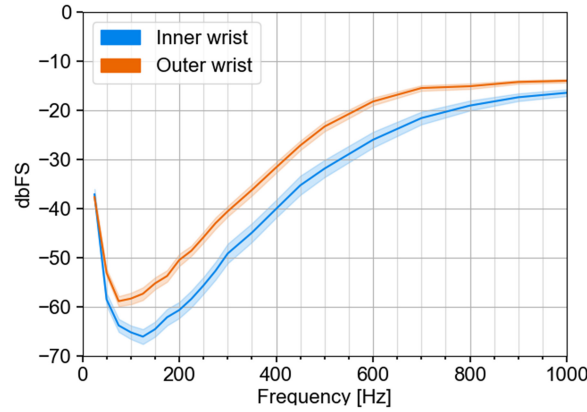


Fig. 5. Results from the experiment measuring the vibrotactile threshold at the wrist. The lowest threshold and thus peak sensitivity is observed at 75 Hz and 125 Hz for the outside and inside areas of the wrist, respectively. The maximum sensitivity range at transmitted frequency is observed at approx. 50–300 Hz and 50–225 Hz for the inside and outside of wrist, respectively. Shaded areas depict the standard error of the mean in each case.

the measured threshold levels averaged across all subjects, for all considered frequencies. The resulting broadband acceleration was measured using the accelerometer and a Bruel and Kjaer 2270 handheld sound analyzer.

3 RESULTS

Figure 5 shows the average detection thresholds in terms of signal amplitude as a function of frequency for both the inside and outside of the wrist. The graph shows that the thresholds for both sides essentially follow the same trend with sensitivity peaking at 75 Hz and 125 Hz for the outside and inside of the wrist, respectively. As predicted, the glabrous skin on the inside of the wrist shows more sensitivity to vibrotactile stimulation than the hairy skin on the outside. An approximately 10 dB difference in the sensitivity of the two skin types is observed at the peak and during roll-off towards higher frequencies. However, the results show little to no difference at lower frequencies (25 and 50 Hz). A -50 dB FS signal amplitude, or less, is observed at ranges 50–300 Hz, for the inside of the wrist, and 50–225 Hz, for the outside of the wrist, allowing at minimum a 50 dB signal amplitude dynamic range for the respective frequency bands.

To assess the statistical significance of our results, we performed a two-way repeated measures ANOVA, where the factors were the stimulated location (outer or inner wrist) and stimulation frequency and the dependent variable was the signal amplitude for measured threshold. First, there was a large main effect of stimulation location ($F(1,28) = 34.01$, $p < .0001$, $\eta^2 = .548$). Second, there was a large effect of stimulation frequency ($F(20,560) = 894.3$, $p < .0001$, $\eta^2 = .97$). Third, the interaction between the two factors was significant ($F(20,560) = 9.04$, $p < .0001$, $\eta^2 = .244$), simply indicating that the effect of stimulation location was not quite constant as a function of stimulation frequency, as it started to drop off sooner for the outside than for the inside of the wrist.

Although most participants showed a similar trend across frequencies, there were considerable differences in the sensitivity level across individuals. Some difference was observed in the results across age and gender, with older participants and male participants generally showing a higher threshold than females and younger participants. However, it should be noted that there was no balancing between participants' age groups and an uneven gender by age group ratio, with mean age for males being higher than the mean age for females. To be able to draw strong conclusions from this ratio, the experiment would have to be repeated with a higher number of participants, more evenly distributed with regards to demographic factors.

The results of the acceleration measurement, which relate the threshold signal levels to acceleration intensity at the skin, as described in Section 2.5, are shown in Figure 6. The acceleration curves follow a similar trend as the

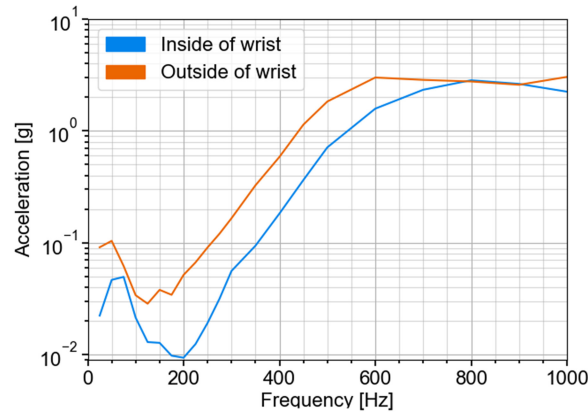


Fig. 6. Measured acceleration values for the average subjective vibrotactile thresholds.

signal amplitude curves in Figure 5, where the lowest acceleration levels, i.e., the highest perceptual sensitivity, is found in the frequency range of 100–275 Hz for the inside of the wrist and 75–250 for the outside. In these frequency ranges, the acceleration is around 0.01–0.03 g for the inside of the wrist and around 0.03–0.09 g for the outside of the wrist. For frequencies below 800 Hz, the acceleration is lower for the inside of the wrist, again indicating that this part of the skin is more sensitive. The lowest acceleration is at 125 Hz at the outside of the wrist but at 200 Hz for the inside of the wrist. For both the inside and outside positions of the actuator, the acceleration amplitude varies by more than two orders of magnitude between the lowest and highest amplitudes. Note that the accelerometer used in the acceleration measurement will have some influence on the acceleration output measured at the skin, where the added mass of the meter when mounted on the actuator will cause a slight decrease in vibration amplitude.

4 DISCUSSION

Our aim in the research presented here was to measure the vibrotactile thresholds at the wrist using the parallel vibration L5 voice-coil actuator. Our ultimate aim is to develop a tactile stimulation device to augment the music experience of cochlear implant users, and this necessitates the investigation of the basic characteristics of the stimulation as a function of frequency to cast light on the effective frequency and dynamic range afforded by this stimulation device. The presented results allow us to draw considerable conclusions that can be used for optimizing the ultimate design.

The results show a clear difference in vibrotactile detection thresholds on the inside and outside of the wrist. The threshold of the glabrous skin on the inside of the wrist is predictably lower than the threshold of the hairy skin on the outside. Interestingly, the results also indicate a difference in the frequency perception of the two sides, with maximum sensitivity observed at a higher frequency for the inside than for the outside of the wrist. For the inside of the wrist, peak sensitivity is observed at 200 Hz. This is consistent with results from previous studies measuring parallel vibration detection thresholds [4].

In many tactile threshold measurement studies in literature, peak sensitivity is determined from the displacement minima of a vibrating object. While it is logical to draw conclusions about tactile thresholds in terms of displacement when the object vibrates normal to the skin surface, and the skin's receptors are thus stimulated by the object pressing on the skin, it does not necessarily apply to parallel vibration. Rather, we feel that a better descriptor of the stimulation from parallel vibration is acceleration, another common unit of measurement for vibration that, together with the object mass, directly relates to the force experienced from the object. From the acceleration measurements, we consider the maximum sensitivity range to be 100–275 Hz. Within this range the

acceleration level is no more than +10 dB relative to the peak sensitivity. Peak sensitivity for the outside of the wrist, however, is measured at 125 Hz, with the +10 dB range spanning 75–250 Hz.

While any reasons for this difference in peak sensitivity are unknown, we wish to point out that at lower frequencies vibrotactile detection in hairy skin depends on hair follicles, while glabrous skin perception is carried by Meissner corpuscles. At higher frequencies the Pacinian Corpuscles appear to be responsible for vibrotactile perception in glabrous skin. Pacinian corpuscles are, however, not found in superficial hairy skin but are present in the deeper underlying skin [21]. We speculate that the difference in peak sensitivity may reflect these differences in mechanoreceptor layout in glabrous and hairy skin. Our finding of higher sensitivity for the inside of the wrist (which has glabrous skin) than the outside (which has hairy skin) is in line with previous psychophysical findings [21, 28] and also with findings from physiology that show how receptor density is higher in glabrous than hairy skin [3, 23]. We should note that, interestingly, our findings appear to contrast with findings reported by Donahue & Letowski [7], who found that for Suvag Vibar vibrators sensitivity was higher for the outside of the wrist than the inside. While the reason for this discrepancy is unclear, we note that our findings were consistent across 30 participants, while they only tested 5 participants, and that, second, they found little or no difference for Siemens Fonator vibrators. While it is tempting to conclude that some particulars of the experimental setup in Donahue & Letowski may explain the discrepancy, this issue is unresolved.

All participants follow a similar trend in their threshold curves. Notably, however, the threshold values vary considerably between individuals. In the case of inner wrist measurements at average peak sensitivity (200 Hz) the lowest threshold measured was at −74.26 dB FS and the highest at −40.66 dB FS. While these differences may reflect noise in responding or measurement errors, they may also imply that to optimize a tactile device for a specific user, the user's vibrotactile threshold values should be determined beforehand. Also, it is important to do this at the intended stimulation location, using the specific actuator of choice. Further examination of individual differences may resolve this issue.

With regard to the question of which spatial location on the skin is optimal, our data does not provide an answer, except that glabrous skin may—other things being equal—be better. But the findings of Lee et al. [17] suggest that outer stimulation on the outside of wrist may lead to better sensitivity. Note that Lee et al. did not test the inside of wrist, so further experimentation is clearly needed to draw firm conclusions.

While many devices have been developed for conveying information through tactile feedback, a drawback in many cases is that the modulation transfer function of the device in combination with the stimulation site is not considered specifically, and this can lead to non-optimal designs. In this study, frequencies of 75 Hz and 125 Hz required the lowest signal amplitudes to generate a response. Due to the non-flat response of the voice-coil in the frequency range of interest, peak sensitivity was not perceived at the respective frequencies in the physical vibration. This clearly emphasizes the importance of taking the nature of the tactile equipment into account during device design.

4.1 Future Work

Future work in the development of the multi-channel vibrotactile device will include more psychophysical research. **Just-noticeable difference (JND)** measurements are planned to determine the appropriate step size in amplitude for each frequency used, which will also cast light on the dynamic range on offer for each frequency. Frequency discrimination tasks and an understanding of the effect of vibrotactile masking when using the L5 actuators will further help with the frequency selection for the device.

Encoding schemes will ultimately be tested and reactions to different vibrotactile pattern presentations of music examined. An interesting addition to the pattern perception research would be to investigate if any of the already-known tactile illusions can be exploited for this purpose. At the time of writing, we have replicated the intensity order illusion as presented by Hoffman et al. [11] using the L5 actuators. Using ERM motors for tactile stimulation, Hoffman et al. showed that varying the intensity of the motor caused localization errors, where a

weak stimulus followed by a strong one resulted in an upward movement sensation and vice versa. Using the L5 voice-coil actuators, we were able to determine that the intensity order illusion is caused by changes in vibration amplitude and not frequency [22].

4.2 Summary and Conclusions

The presented results confirm that maximum sensitivity to parallel vibration of the glabrous skin is around 200 Hz. This also applies to flat surface actuators such as the L5 voice-coil by Lofelt GmbH. Our findings suggest that maximum sensitivity for hairy skin is at a lower frequency, 125 Hz at the specified location (outside of the wrist). When designing a vibrotactile stimulation and feedback solution, it is important to keep in mind that different frequencies will generate maximum response on different body locations, and the vibrotactile threshold values between individuals vary greatly. Therefore, an optimal device may only be attained with individual calibration at the specified body location.

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