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Electrotactile Feedback for Handheld Devices with Touch-Screen and Simulation of Roughness

M. Ercan Altinsoy, and Sebastian Merchel

Abstract— We present a novel electrotactile display that can be integrated into current handheld devices with touch screens. In this display, tactile information is presented to the fingertip of the user by transmitting small currents through electrodes. Experiments were conducted to investigate the perception of simulated textures using this electrotactile display technique. One fundamental feature of texture, which is the focus of this study, is roughness. The aim of the first experiment was to investigate the relationship between electrotactile stimulation parameters such as current and pulse frequency and the perception of roughness. An increase in the current magnitude resulted in an increase in perceived roughness. The aim of the second experiment was to investigate parameter combinations of electrotactile stimuli can be used to simulate textures. Subjects adjusted the intensity and frequency of the current stimuli until the simulated textures were perceived as being equal to reference textures such as sandpapers of varying grit numbers and grooved woods with varying groove widths. Subjects tended to find an electrotactile stimulus with a high current magnitude and a low pulse frequency more suitable to represent rough surfaces. They tended to find just-perceptible current magnitudes suitable for very smooth surfaces and did not show a preference for any frequency.

Index Terms— Mobile devices, touch-screen, electrotactile feedback, roughness perception, texture reproduction.

1 Introduction

The application of touch-screen technology in daily living products is now just emerging due to advances in software flexibility, intuitive handling, space and cost savings. Therefore, in recent years, a variety of handheld devices using touch-screen technology have been developed.

The haptic communication channel plays a central role in touch-screen applications, not only as an input channel but also as an output channel. For example, tactile feedback that confirms a successful operation is important to avoid user dissatisfaction and high input-error rates [1,2]. Additionally, tactile feedback can enrich the user experience during scrolling or touching events [2,3].

Several studies have concentrated on technical solutions for tactile feedback implementation in electronic devices using small vibration actuators [4, …,9]. Eccentric mass (pager) motors are one of the most used actuators in mobile phones. Electromagnetic moving coils and piezoelectric actuator solutions have also been used to generate vibrotactile feedback [4,7]. Important physical properties of tactile feedback that strongly influence the feedback quality of the actuator include the bandwidth of the device, the frequency response, the maximum feedback amplitude, the resolution and the latency. Localized tactile feedback on the fingertip, which is required for high-quality feedback, cannot be easily realized with most of the available actuators. Piezoelectric-beam-type actuators are one of the exceptions [10]. Eccentric mass motors have strong limitations in frequency response and maximum feedback amplitude [4,10]. However Yao et al. found that the overall perceived vibration strength is affected by both the weight of the device and the underlying driving frequency; in summary, a heavier mobile phone results in a greater perceived vibration strength [8]. The suspension of the haptic touch screen in hand-held devices is also an important issue. Thin, planar suspension systems, which provide the desired isolation of haptic effects to the touch screen have been developed [11].

Recently, composite piezoelectric actuators have been used to provide vibrotactile haptic feedback to touch screens [12]. Generally, composite piezoelectric material contains piezoelectric ceramic fibers embedded in a certain pattern within a polymer matrix. They can be formed as "haptic tape", and therefore, can be used as a sealant between two components. Composite piezoelectric actuators allow optimization of the parameters such as mechanical strength, stiffness, damping coefficients, toughness, flexibility, and displacement to length ratio, and can serve as a viscoelastic suspension for a touch screen. However, moving (physically vibrating) components might be error-prone and challenges exist in terms of durability.

Another actuator type is electromagnetic shaker. Although electromagnetic shakers have good frequency-response characteristics, their size is comparatively large and their mass is high [4].

To overcome the technical limitations of electromagnetic actuators, different technologies have been developed and implemented in handheld devices. Electroactive

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polymer technology (EAP) is one of them [13]. EAPs exhibit size or shape change when electrically excited. They can be constructed in different configurations to generate motion along the x, y or z axis. EAPs are attractive due to their light weight and low cost. However, the requirement of the high voltage is one drawback of this technology. In recent years, researchers have focused on the mass production of the EAPs and the reduction of the required activation voltage.

To effectively stimulate the mechanoreceptors within skin, shear stress can be used instead of stimulation of skin by vertical vibration. Nara et al. developed a surface acoustic wave (SAW) tactile display to modulate the shear stress [14]. Two interdigital transducers generate standing or progressive waves on a lithium niobate (LiNbO3) substrate. The user explores the substrate with a slider that has 100 steel balls on a thin tape. The steel balls provide distributed points to which stress is applied on the finger surface. The burst frequency of the SAW is used to control the stick-slip frequency. In this way the fineness of the grain of the surface can be controlled. The experiments showed that a SAW tactile display can simulate rough or smooth surfaces. The disadvantage of this system is that it consists of a large amount of moving elements.

A tactile pattern display (TPaD) is another technology for creating texture sensations through variations in surface friction [15]. A very thin piezo ceramic disk is epoxied to a glass disk. Across the glass disk, the haptic sensations can be generated through the modulation of the shear forces acting on the finger. In other words, TPaD employs ultrasonic vibrations to create a squeeze film of air between the vibrating surface and the fingertip, thereby reducing the friction. Through this method, tactile feedback can only be provided for sliding contact. In addition, challenges might rise to homogenously generate feedback on large and thin surfaces. Recently, studies were conducted to enhance this approach (ShiverPaD, [16] and LATPaD [17]).

In this study, an electrotactile display was developed to create tactile sensations. The advantages of such electrotactile displays are that they contain no moving components, they maintain good contact with the skin, they enable homogenous feedback, they allow excitation for static and sliding contact, and they are silent.

Electrotactile displays deliver very weak, controlled current pulses to embedded electrodes. In this way, they can produce touch sensations at the location of the electrode by passing a small electric current through the skin [18]. Previous studies have shown that electrotactile stimulation directly excites the mechanoreceptive afferent nerve fibers and produces sensations that are described as vibration, buzz, pulsation or pressure [19]. The current and frequency of the stimuli are important parameters influencing the quality of the perception [20].

In recently developed electrostatic or electrovibration displays [21, 22, 23, 24], there is no direct contact between the finger (body) and the electrode. The conductive surface is covered with an insulating layer. Therefore, the excitation principle and the signals differ from electrotactile displays. Electrostatic stimulation is based on mechanical excitation induced by electrostatic force, whereas electrotactile stimulation is based on the excitation of the cutaneous nerve fibers with electric charge.

The most commonly used electrotactile displays are matrix displays which consist of a number of small (e.g., 1 mm^2), closely spaced electrodes [25, 26, 27]. This can cause a short-circuit in practical applications. In addition, the control of electrode arrays is a difficult issue. Thus, these arrays are not suitable for handheld devices with touch screens. The comfort of the electrotactile percepts is affected by the electrode geometry, skin condition, and stimulus waveform [26]. Considering that larger electrodes tend to produce more comfortable sensations than smaller ones, a large-electrode solution was chosen in this study rather than a pin-array solution.

Handheld devices with touch-screen technology would benefit from being able to convey textural information during the exploration of virtual objects or scrolling events. In this study, two psychophysical experiments were conducted to determine the optimum electrotactile stimulation parameters for texture reproduction.

Texture perception is an important exploration mechanism humans use to identify objects and their properties. Surface roughness is the most important physical and perceptual determinant of texture perception. Therefore, most studies related to human response to textures have concentrated on the investigation of roughness perception. Based on psychophysical studies on roughness perception, textures can be categorized and simplified into two different stimulus categories: raised dots, e.g., abrasive surfaces such as sandpaper, and grooved surfaces, e.g., a vinyl LP record. In one of the earliest psychophysical study on tactile roughness perception, sandpapers of various grades were used as stimuli [28]. Stevens and Harris found that the perceived roughness of sandpapers increases with decreasing grit number. A later psychophysical study focused on the other type of stimulus, the grooved surface. In Lederman and Taylor's (1972) experiments, subjects made magnitude estimates of the perceived roughness of grooved aluminum plates by actively moving three fingers across the surfaces under conditions with controlled finger force [29]. Their results indicated that apparent roughness tends to increase as the grooves are widened, as the finger force increases, and as the spacing between the grooves narrows.

Due to the development of haptic devices and the fact that the tactile sense is included in multimedia applications, the research on roughness perception via a haptic interface became more important. Most of the studies in this field have been based on force-feedback devices such as joysticks or phantom devices [30, 31, 32] and vibrotactile actuators [5, 33]. Campion and Hayward described an efficient technique, the "MOdified Binary Search", for adjusting the subjective experience of roughness produced by different haptic devices or texture synthesis algorithms [34].

2 Electrotactile Display

An electrotactile display system consisting of two layers was implemented for the augmentation of tactile sensations (Figure 1). The first layer is an optically transparent electrode that is placed on the touch screen (i.e., the front side of a handheld device). The second electrode is an electrically conductive part or coating, which can be the metal rear panel of the device. If the user holds the device in his hand, he has a large-area contact with the metal rear panel (second electrode). If he now contacts the touch screen (first electrode) with his fingers, a local electric current passes through the skin, and the subcutaneous potential distribution excites the mechanoreceptors. The electric current is adjusted to excite a pleasant tactile sensation at the small area of contact at the first electrode. This current runs through the body and is distributed over a large area of contact at the second electrode. Therefore, no tactile sensation is excited at the second electrode.

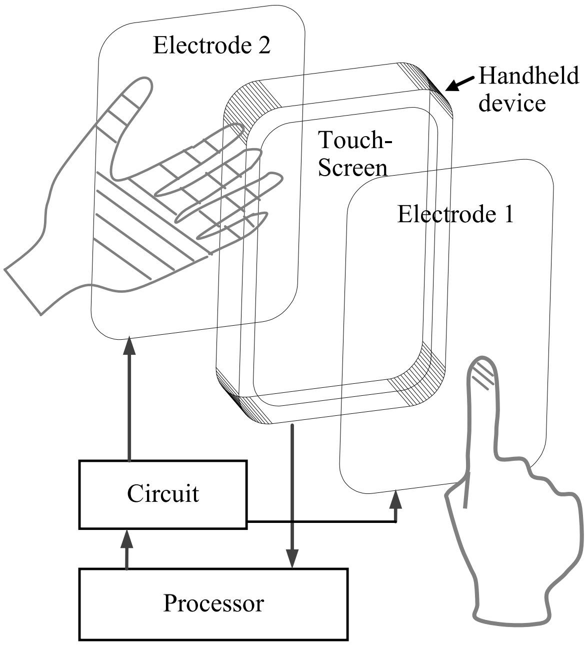

Fig. 1. A schematic representation of the electrotactile display system with a handheld device. The processor and the circuit unit are integrated into the handheld device [33].

According to the touch position and, e.g., the amount of pressure applied to the touch screen, an electrical signal will be determined by a processor. Sweat and the contact properties have a significant impact on electrode-skin impedance [36]. Therefore they can cause an alteration of the tactile feedback intensity and quality. In recent years, various technologies have been developed to solve this problem [36, 37]. To ensure a uniform stimulation, the influence of the contact and body resistances should be minimized. For example, single- or dual-handed operation of the device can cause differences in resistance. Therefore, current-controlled pulses are delivered to the electrodes. For this purpose, a transconductance amplifier was implemented based on a circuit described by Schaning and Kaczmarek [37]. Stable bipolar output currents up to ± 20 mA can be provided with an output resistance of 8.8 MΩ and voltages up to ±600 V. This enables consistent electrotactile stimulation independent of moisture of the skin and size of contact area.

3 Motivation of The Psychophysical Experiments

The aims of the experiments described in the following sections were to determine if it is possible to simulate haptic surface textures using an electrotactile display. The first experiment was conducted to investigate the relationship between electrotactile stimulation parameters such as current and pulse frequency and roughness perception. The purpose of the second experiment was to determine parameter combinations of the electrotactile stimuli that can be used to simulate textures.

4 Experiment I

4.1 Subjects

Ten subjects, four men and six women, aged between 22 and 27 years, participated in the experiments. The subjects were paid on an hourly basis. All subjects were right handed and had no known hand disorders. No subject with a heart pacemaker participated in the experiments. They used their right hand in the experiments.

4.2 Stimuli and Procedure

Current magnitude (mA) and pulse frequency (Hz) of the electrotactile stimulus are the parameters allowing the designer to represent texture profiles of different roughnesses. Stimuli were chosen with various unipolar current magnitudes I (10, 15, 20, 25, 30, 35 and 40 mA) and frequencies (30, 50, 75, or 100 Hz). 10 mA current magnitude for 30 Hz, 50 Hz and 75 Hz is imperceptible for 90% of the subjects, therefore these conditions are removed from the stimulus pool. The stimulus 100 Hz 40 mA was uncomfortable for some subjects, therefore it is also removed. Fig. 2 shows the waveform of the stimuli. The currents used in this study are comparable to currents used in medical devices, e.g. for muscle stimulation and lower than standardized safety limits [38].

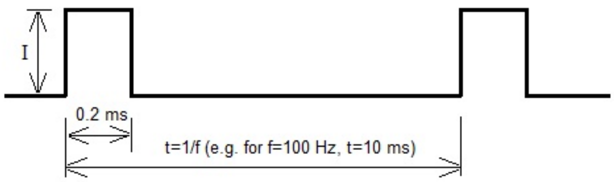

Fig. 2. Waveform of the electrotactile stimulation. I, is the current of the pulse with a pulse duration of 0.2 ms, and t is the duration between two pulses, which is frequency-dependent.

An electro-tactile display unit (see Section 2) was used to represent the texture information. However, in this experiment it was not crucial to provide visual information through the display. Thus, a thin copper foil was used as the first and second electrode. The surface of the electrodes was extremely smooth (RMS roughness is about 0.7 µm). The size of the electrodes corresponded to a typical handheld device (10.5 cm x 6.8 cm). A resistive touch screen that had the same dimensions was used.

Subjects were instructed to move their finger with a constant velocity of 10 cm/s which was controlled visually by the experimenter during the experiment. The virtual textures were presented and roughness was estimated using an absolute magnitude estimation method [39]. The subjects' task was to report the degree of perceived roughness using numbers. For the first stimulus, they were asked to assign any positive, nonzero number (i.e., a decimal, a fraction or a whole number) that they considered appropriate. For the next stimulus, they were asked to give an appropriate number in relation to the previous stimulus (rational). In other words, if the second texture felt twice as rough as the previous stimulus, they should assign a number which is two times the number they had assigned to the previous stimulus. The subjects were instructed not to worry about being consistent.

In the training phase, which took approximately 15 minutes, all participants were first presented with different stimulus combinations from across the full stimulus range and then they were familiarized with the magnitude-estimation procedure using six different stimulus combinations. To prevent participants devising a fixed response range, they were informed that they might experience rougher or smoother stimuli in the actual experiment than in the training. In the actual experiment, each stimulus was presented four times in a random order.

4.3 Results

The psychophysical roughness functions for the pulse frequencies 30 Hz, 50 Hz, 75 Hz, and 100 Hz as a function of current magnitude are shown in Figures 3, 4, 5 and 6, respectively. In all figures, the x-axis indicates the current magnitude (mA) and the y-axis indicates the roughness estimates. The data points represent means (geometric) and are based on 40 responses. The method of least squares was used to determine the psychometric functions. The r^2 values for the 30 Hz, 50 Hz, 75 Hz, and 100 Hz conditions were 0.92, 0.94, 0.97 and 0.95, respectively.

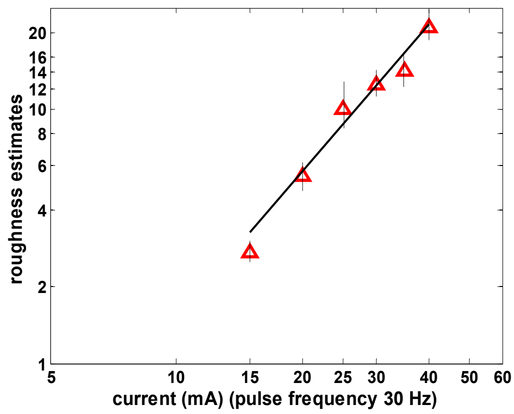

Fig. 3. Perceived roughness as a function of current for 30 Hz pulse frequency.

For all frequencies tested (30 Hz, 50 Hz, 75 Hz and 100 Hz), the perceived roughness increased with increasing current. E.g., for the 100 Hz pulse frequency, the estimated roughness value was 2.7 for the 10 mA current and it increased up to the value of 23.1 for the 35 mA current. This increase was also observed for the 75 Hz, 50 Hz and 30 Hz conditions.

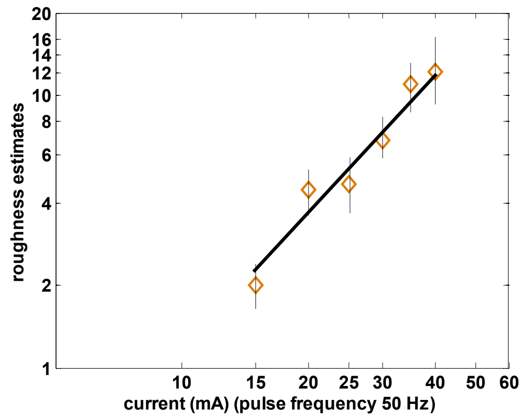

Fig. 4. Perceived roughness as a function of current for 50 Hz pulse frequency.

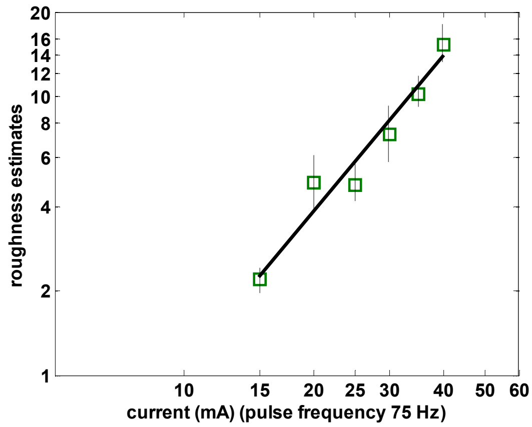

Fig. 5. Perceived roughness as a function of current for 75 Hz pulse frequency.

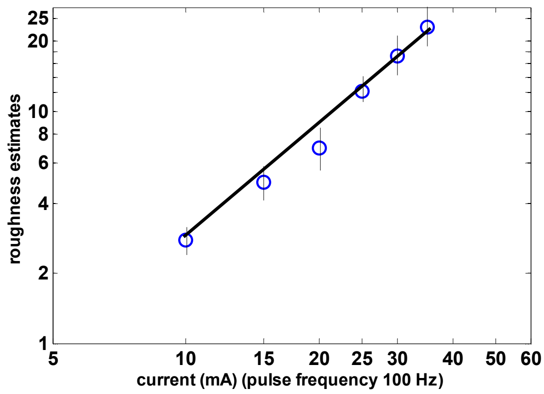

Fig. 6. Perceived roughness as a function of current for 100 Hz pulse frequency

An additional experiment was conducted to investigate the influence of frequency on the roughness perception. In this experiment the current was constant 25 mA with varying frequency.

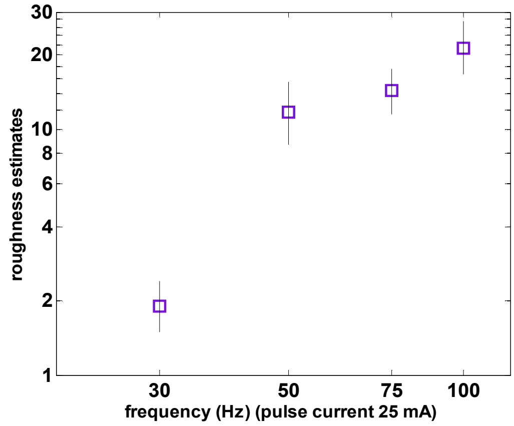

Fig. 7. Perceived roughness as a function of frequency for 25 mA pulse current.

Comparing the roughness estimates in all four frequencies, we observed that the roughness estimate for the 100 Hz condition was higher than the roughness estimate for the 30 Hz or 50 Hz conditions (Figure 7). These observations indicate that the frequency plays a role in the roughness estimates.

4.4 Discussion

The results show that an increase in the current magnitude resulted in an increase in perceived roughness. The same tendency was observed for an increase in the pulse frequency. Perceived roughness increased with increasing frequency. Psychophysical roughness functions are approximately linear in both cases (for current magnitude and frequency). The perceived roughness results as a function of frequency are based on a constant pulse current of 25 mA. These results should be verified for other current values in future experiments.

A few subjects complained that they have confused their judgments because of intensity & pulse-frequency variation. They reported that if they imagined realistic surfaces and their roughness, for the roughest surfaces the stimulus was very intensive but at the same time it had low frequency. These complaints lead the author to conduct further experiments to investigate the perceived roughness of the electrotactile stimulus as compared to realistic surfaces. The comparison of real and simulated textures has been used also in vibrotactile studies [14, 34, 40]. This investigation will help to interpret the results of the first experiment and also supply useful data for the designers.

5 Experiment II

Taking into account the results of the first experiment, which aimed at investigating the relationship between stimulation current, pulse frequency and roughness perception, further experiments were conducted. As previously explained, the aim of these experiments was to investigate the perceived roughness of the electrotactile stimulus compared to real textures. Therefore, texture profiles commonly used in psychophysical studies, i.e., sandpaper (raised dots) and grooved woods (gratings) were selected as stimuli.

5.1 Subjects, Stimuli and Procedure

The same subjects participated in the second experiment. Two different kinds of stimuli were used in this experiment. The first group of stimuli consisted of eight different sandpapers with varying grit numbers: 60, 120, 150, 220, 320, 500, 800 and 1000. The second group of stimuli consisted of rectangular wood pieces, 14 × 4 × 1.5 cm, each with a set of linear grooves (spaced at 0.25, 0.375, 0.5, 0.625, or 0.75 mm) with a constant 1.00 mm ridge width.
The aim of this study was to investigate the point of subjective equality. Therefore an adjustment technique was applied as the measurement method. Real textures were explored by the subjects by moving the tip of their right index finger across the surfaces. They then explored the simulated textures by touching the screen (second electrode). Subjects were instructed to move their finger with a constant velocity of 10 cm/s which was controlled visually by the experimenter during the experiment. The subjects has adjusted the intensity and frequency of the simulated textures (the electrotactile stimulus, a square waveform) until it was perceived as being equal to the reference real texture (sandpaper or grooved wood). The subjects were first asked to adjust the frequency and then the intensity of the stimulus. Subjects were blindfolded (the experimenter helped the subjects to reach the real surfaces) and wore closed damped headphones to eliminate any touch-associated sounds. In the training phase, which took approximately 15 minutes, all participants were first presented with several electrotactile stimuli at different frequencies and intensities. After the training, each realistic stimulus was presented four times in a random order.

5.2. Results

The PSE (point of subjective equality) values of the sandpaper stimulus and their standard errors are shown in Figure 8. In this figure, the x-axis indicates the pulse frequency and the y-axis indicates the current magnitude. Each grit number is represented by a different symbol.

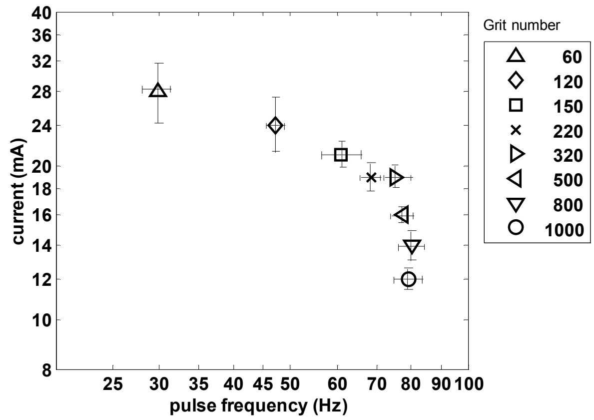

Fig. 8. Adjusted current (mA) and pulse frequency (Hz) values for sandpapers with varying grit numbers.

Current magnitudes and pulse frequencies as adjusted by the subjects during the test were averaged across all subjects and trials for each grit number. Single-factor repeated measures ANOVA tests were conducted separately for current and pulse frequency. The Greenhouse-Geisser adjusted degrees of freedom are reported. The ANOVA tests show that the grit number had a significant effect on the current ($F(2.59, 23.39) = 94.88$, $p < 0.0005$) and pulse frequency ($F(1.05, 9.45) = 47.16$, $p < 0.0005$).

The PSE values of the grooved wood stimulus and their standard errors are shown in Figure 9; here, each groove width is represented by a different symbol. The adjusted current magnitudes and pulse frequencies were averaged across all subjects and trials for each groove width. The single-factor repeated measures ANOVA tests indicate that the groove width had a significant effect on the current ($F(2.54, 22.87) = 350.37$, $p < 0.0005$) and pulse frequency ($F(2.82, 25.39) = 1583.32$, $p < 0.0005$).

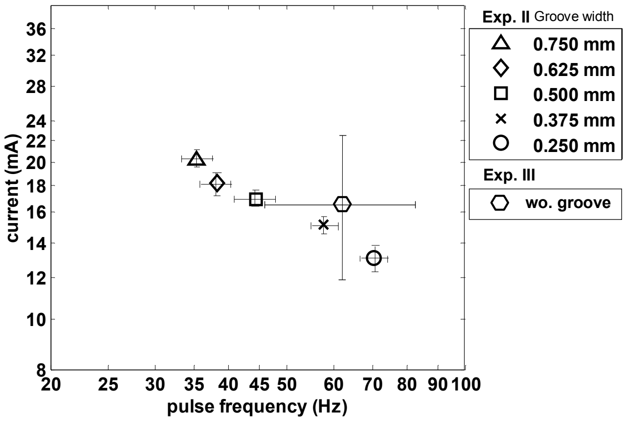

Fig. 9. Adjusted current (mA) and pulse frequency (Hz) values for the grooved woods with varying groove widths.

5.3 Discussion

The results of the second set of experiments indicate that it is possible to simulate different textures using electrotactile stimuli. The perceived roughness of the virtual textures is a function of the current level and the pulse frequency. This result is in line with the results of other roughness perception experiments, which use pin array [40] or phantom device [31] to simulate textures. The results of the “sandpaper” experiment show that an increase in grit number resulted in subjects decreasing the current magnitude and increasing the pulse frequency to match the texture. For example, for grit number 60 the current was 28 mA and the pulse frequency was 29 Hz, whereas for grit number 800 the current was 14 mA and the pulse frequency was 81 Hz. The results of the “grooved wood” experiment show that an increase in groove width caused subjects to increase the current magnitude and decrease the pulse frequency. For example, for the 0.750 mm groove width, the current was 20 mA and the pulse frequency was 35 Hz, whereas for the 0.375 mm groove width the current was 15 mA and the pulse frequency was 57 Hz. The difference in the adjusted frequency for the grit numbers 320, 500, 800 and 1000 was very small in comparison to other grit numbers. For those grit numbers with a small adjusted frequency difference, the current seems to be dominant parameter. One reason for this difference may be that it was not easy for subjects to feel frequency differences for such high grit numbers.

6 Experiment III

6.1 Subjects, Stimuli and Procedure

Following Experiment 2, an experiment was conducted to investigate the suitable current intensity and frequency for very smooth surfaces. Fourteen subjects, eight men and six women, aged between 18 and 32 years, participated in this experiment. The procedure was the same as that in the previous experiment. the subjects were presented with a wood plate without any grooves (RMS roughness is 5.6 μm) and asked if they could find a suitable electrotactile stimulus for it.

6.2 Results

The PSE-value is shown in Figure 9. The results show that the standard deviation for frequency is very high. Subjects tended to find just-perceptible current magnitudes suitable for very smooth surfaces and they did not show a preference for a certain frequency.

7 General Discussion

A comparison of the results of the first and second set of experiments provides information that is relevant to the design of haptic interfaces. In cases where subjects did not have a realistic criterion, they tended to perceive the simulated surface as rougher when the current or pulse frequency of the electrotactile stimulus, or both, were increased. However, if comparison is made with real surfaces, subjects tended to find an electrotactile stimulus with a high current magnitude and a low pulse frequency to be a better simulation of rough surfaces (such as grit number 60 sandpaper or grooved wood with a groove width of 0.75 mm).

The change of skin impedance due to sweat or the change of body impedance due to single- or dual-handed usage should be taken into account when using electrotactile feedback devices. In this study, a transconductance amplifier was used to ensure a uniform stimulation. Other comparable technologies are available to stabilize the stimulation [36].

Continuous electrotactile stimulation can cause sensory adaptation. The duration of the stimuli in this study was short which prevented adaptation problems. In possible applications of electrotactile displays, the adaptation should be taken into account if long-duration stimulation (>1 min) is requested [41, 42]. However, monophasic stimulation results in less adaptation then biphasic pulses. The time course of threshold elevation (10-20 min to reach asymptote) for electrotactile stimuli is similar to vibrotactile stimulation [41].

8 Conclusions

This study introduced a novel electrotactile display that can be integrated into current handheld devices with touch screens. This technology is promising for different multimodal devices because it contains no moving components, it maintains good contact with the skin, and is silent. Two experiments were conducted to determine the stimulation parameters for the texture reproduction. The results of the experiments provide guidelines for designers to create plausible virtual haptic textures using electrotactile technology.

The proposed technology requires the user to have dual-handed contact with the device. Therefore, if the device is on a table and the user has only single-handed contact, the user will have no tactile feedback. The situation is similar, if the user wears a glove on one hand.

In this study, a fixed finger speed was used to investigate fundamental effects. In a practical application, speed dependent stimulation might be required. The influence of the finger speed on the parameters of the matched electrotactile stimulus needs to be further examined. In the experiments, subjects applied gentle pressure during the exploration of the real and simulated textures. Future investigations will have to consider other exploration force conditions (particularly high pressure). We also plan further investigations to extend this work to include other feedback forms, e.g., virtual buttons.

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