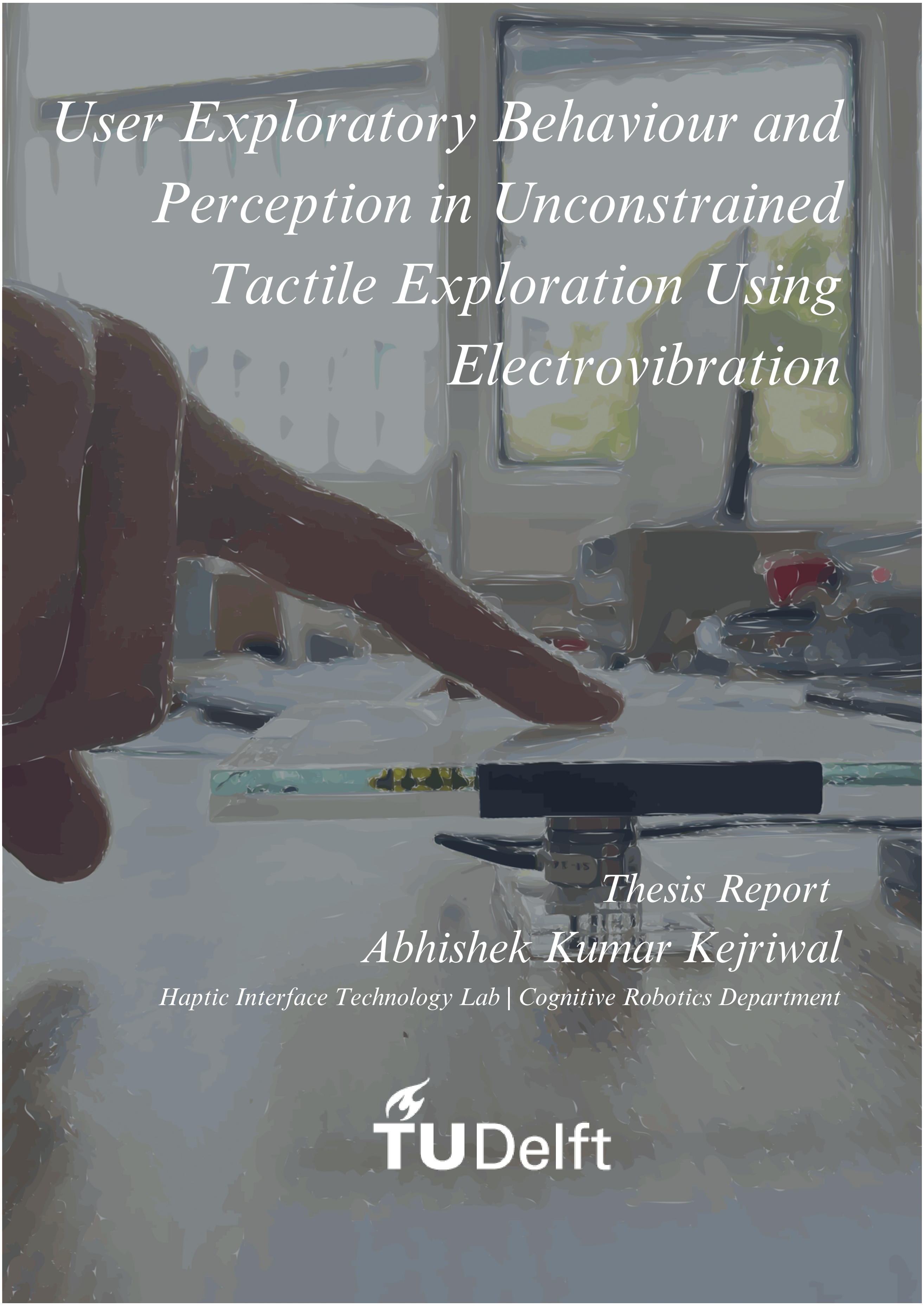

User Exploratory Behaviour and Perception in Unconstrained Tactile Exploration Using Electrovibration

Thesis Report

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User Exploratory Behaviour and Perception in Unconstrained Tactile Exploration using Electrovibration

Master's Thesis Report

by

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Preface

My decision to pursue an M.Sc. in Robotics Engineering at TU Delft marked an important transition from my roots in automotive engineering and my home country. These past two years have been a blend of enriching education and challenges. I've evolved both academically and personally, learning from both my mistakes and accomplishments. This thesis is a product of not only my own efforts, but also the persistent support and guidance I received. I am grateful to everyone who contributed to achieving this milestone and would like to take a moment to thank each one of them sincerely for making this dream come true.

I want to express my gratitude to Prof. Dr. Yasemin Vardar. I recall being captivated by your guest lecture on Haptics for the HRI course. Meeting you for the first time in-person at the Master's thesis market, I was nervous but certain that I wanted to explore the field. Although I was aware that I might not have been the ideal candidate based on my experience in this domain, my dedication and commitment never wavered. I am thankful for all your help and guidance throughout this journey.

A big thank you to Jagan for the countless meetings and constant encouragement to keep going. Your inputs have been extremely valuable. I must also extend my heartfelt thanks to Prof. Dr. Joost de Winter. Your willingness to take time out of your busy schedule to provide detailed feedback and unwavering support was crucial to the development and improvement of my work.

I would like to thank Mrinal for inspiring me always and for having my back regardless of the circumstances. The feeling of gratitude is also due to my friends Aniruddha, Arun, Saransh, Anitej, Yash, Prakhar, and all my friends back in India for their constant encouragement, insightful discussions, and constant camaraderie.

Lastly, my heartfelt gratitude to my parents, siblings, and uncle. As I pen this, I am overcome with emotion, knowing that this accomplishment is equally mine and yours. Your support and love have been my rock. You have empowered me to pursue my ambitions freely and provided me with the means to ascend. Your sacrifices, Maa and Dady, are the silent yet formidable forces behind all of my achievements. I promise to honor this gift and strive each day to make you proud. This one's for you.

Abhishek Kumar Kejriwal
Delft, October 2023

CONTENTS

User Exploratory Behaviour and Perception in Unconstrained Tactile Exploration Using Electrovibration

Abhishek Kumar Kejriwal, Jagan Krishnasamy Balasubramanian, Joost de Winter, and Yasemin Vardar

***Abstract*—Electrovibration offers potential to enrich virtual touch experiences with authentic tactile sensations on touchscreens. In controlled environments, responses to tactile stimuli may be anticipated, yet this predictability becomes uncertain in unconstrained settings due to dynamic factors like varied applied force, finger scanning speed, and sensory adaptation. To address this issue, we conducted a psychophysical study with 21 participants to investigate the effect of tactile rendering parameters on user exploratory behaviour and perception during unconstrained exploration of artificial textures, aiming to discern a predominant tendency of interaction. Our results revealed, signal amplitude shapes human tactile perception considerably during unconstrained exploration. We also observed, higher signal amplitudes were associated with lower finger scanning speeds, a trend tempered by significant individual differences, thereby affecting its practical effect. In contrast, the measured applied normal force and obtained finger movement pattern remained consistent and were not affected by different tactile rendering parameters. Notably, the rate of change of measured lateral force was found to be a better metric for the perceived tactile dimensions than the lateral force magnitude. These findings enhance our understanding of perception and physics of such interactions, that could be vital for designing and delivering improved haptic feedback on electrovibration-based tactile interfaces.**

***Index Terms*—Haptics, electrovibration, scanning speed, applied normal force, exploratory behaviour, adaptability, unconstrained exploration, virtual texture perception**

I. Introduction

THE last twenty years have observed a remarkable growing interest in designing and creating touch-based surface technologies. Research and end-user group's focus on touch-based interfaces has shaped this approach [1]. Smartphones, tablets, smart TVs, kiosks, and digital information displays have integrated touch screens [2]. Smartphones are now essential to modern life, making it hard to imagine our existence without them. Dynamic, user-friendly interfaces are driving the usage of touch displays in daily life.

Despite their popularity and demand, these modern devices lack dynamic tactile feedback. The lack of authentic tactile feedback in these gadgets has resulted in an increased dependence on visual and auditory feedback. According to a study by Buxton et al. [3], the lack of dynamic tactile input can decrease the authenticity of visual environments, break the concept of direct interaction, and reduce interface efficiency as the absence of tactile feedback makes it difficult for the user to use the device efficiently.

Given the importance of dynamic tactile feedback on touch-based interfaces, researchers worldwide are investigating strategies to provide perceptually valid tactile sensations on touchscreens to improve their usability [4]. One technique for creating tactile interfaces for touch surfaces is *electrovibration*, which uses friction modulation in the tangential plane between the touch surface and the sliding finger to create tactile interfaces for touch surfaces without mechanical actuation [5]. Electrovibration involves applying a high alternating voltage to a touchscreen's conductive layer to generate electrostatic attractive forces in the normal direction between its surface and a sliding finger, which increases frictional forces on the finger in the opposite direction of finger movement (fig. 1) [1]. By changing the input signal's amplitude [6], frequency [5], and waveform [7], synthetic tactile sensations and even pseudo three-dimensional shapes can be created on a touch screen [2]. A constant tactile sensation is produced by the input signal's uniform propagation pattern in the plate's conductive layer [5]. However, the electrovibration force experienced by the user is localised to the finger contact area and does not spread throughout the touchscreen [1]. This technique is useful for a variety of applications; due to its quick operation, dynamic functionality, low energy consumption, and large bandwidth.

Electrovibration exhibits promising capabilities in generating immersive and accurate touch-screen haptic sensations. The electrovibration technique primarily classifies texture impressions as smoothness/roughness and stickiness/slipperiness [8]. An ideal scenario for designers is to regulate user tactile experiences regardless of their finger scanning speed or applied force [4]. Nonetheless, electromechanical inconsistencies when the finger interacts with the display freely may affect the display's haptic feedback. For instance, when users press harder or scan slower, the contact area between the finger and the surface expands while the air gap between them decreases [9]. This change causes a slight reduction in the total impedance of the resultant electrical model of the finger-touchscreen interaction, a result of increased capacitance and decreased resistance within the system [4]. Theoretically, this should amplify the generated electrovibration force. However, this phenomenon also leads to an increase in the occurrence of stick-slip behaviour, increased stiffness of the finger's skin, and a decrease in the finger's accrued effective voltage [4], [10]. Ultimately, these traits reduce electrostatic force-induced mechanical deformations and tactile feedback, potentially undermining the effectiveness of electrovibration-induced tactile sensations.

Moreover, it is plausible that the tactile information users perceive during these interactions may also influ-

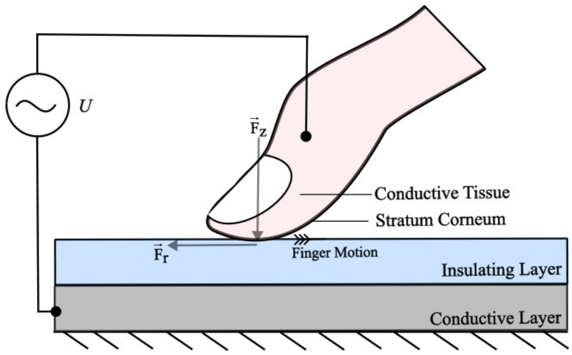


Fig. 1. Electrovibration operating principle

ence their exploratory behaviour, whether consciously or unconsciously [11]. This statement is supported by previous research conducted on real textures, which has demonstrated that users adjust their exploration strategies, such as applied force, scanning speed, and finger movement pattern in response to the surface characteristics of the explored surface, such as its roughness or hardness [12]. However, with the increasing advancement of haptic devices, it is crucial to investigate if similar exploratory tendencies are observed on artificial textures. Additionally, psychophysical tests that investigate the effects of exploratory parameters on tactile perception have consistently controlled user behaviour whereas real-world tactile explorations are active and unconstrained [11]. Hence, it is important to investigate how users explore artificial textures in unconstrained conditions. Gaining insight into the underlying mechanism of haptic perception and understanding how it influences exploratory movements can reveal if users exhibit a common tendency of exploration to improve their tactile feedback experience. This can pave the way for the development of user centric haptic displays tailored for enhanced interaction and experience. Thus, this study aims to address this knowledge gap about identifying a predominant tendency exhibited by the users while exploring an electrovibration display (in terms of finger scanning speed, finger movement pattern, and applied normal force) by investigating two primary aspects: a) the influence of different tactile rendering parameters on user exploratory behaviour, and b) the impact of various tactile rendering parameters on user perception during unconstrained exploration. To answer the same our hypothesis posited:

Users are likely to exhibit a predominant tendency while adjusting their exploratory behaviour to perceive various artificial textures generated using electrovibration technology to improve their tactile feedback experience

For this purpose, we conducted a psychophysical study involving 21 participants to examine their exploratory behaviour and tactile perception across a range of artificially generated textures using different signal rendering parameters. Participants were instructed to freely explore the electrovibration display with their dominant hand's index finger while we recorded their finger position and contact forces. Finally, participants provided subjective ratings for each texture on a set of predefined adjective scales.

The outline of this paper is as follows: Section II offers a brief overview of electrovibration technology, the factors influencing it, the mechanics of tactile adaption and the perceptual mechanisms of the relevant tactile dimensions. Section III elaborates on the experimental methodology designed to explore the two primary aspects defined above. The results of the study are presented in Section IV, which are subsequently discussed in Section V along with the limitations and future work recommendations. Finally, the conclusions are presented in Section VI.

II. Background and Related work

A. Electrovibration and affecting factors

Johnsen & Rahbeck reported the electrical attraction between human skin and a charged surface in 1923 [13] and later by Mallinckrodt et al. [14] in 1953. Using this effect, Strong and Trexel [15] proposed the first touch display in 1970 utilising a polyvinylidene chloride-insulated grid of opaque electrodes. By stimulating each pin with varied voltages, they found that peak applied voltage, not current intensity, determined touch sensation intensity [15]. They also proposed the first mathematical model based on the well-known parallel-plate capacitor theorem to show that the output electrostatic force attracting the finger to the touchscreen surface is proportional to square of the interface voltage differential.

Later, Grimnes et al. [16] called this phenomenon *"electrovibration"*. A study by Beebe et al. [17] developed a polyimide-on-silicon electrostatic fingertip touch display via lithographic microfabrication. The preliminary investigations showed that 200-600 V voltage pulses can cause "sticky" sensations on this thin, robust touch display. Using a similar display, Kaczmarek et al. [18] discovered that individuals were less sensitive to positive electrovibration pulses than negative or biphasic pulses. They explained that human skin's asymmetric electrical characteristics may cause this discrepancy.

Later, Bau et al. [5] demonstrated electrovibration technology on a large commercial touchscreen using transparent electrodes. They measured human sensory thresholds of electrovibration using sinusoidal inputs at different frequencies. The curve of threshold voltage variation as a function of frequency was U-shaped, centered at 180 Hz. Wijekoon et al. [6] showed that the intensity of electrovibration stimulus was logarithmically proportional to the applied voltage signal amplitude. Vardar et al. [7] examined how input voltage waveform affects electrovibration perception. Their results showed that low-frequency square wave signals are perceived as more intense than sinusoidal ones due to their high-frequency components activating the tactile Pacinian psychophysical channel [7]. Kim et al. [19] investigated low-voltage approaches for strong electrovibration perception. They found that a DC offset can increase electrostatic force at low voltages by causing a non-zero mean voltage

Tactile feedback can be generated using electrostatic forces in several other ways on touchscreen surfaces. For instance, using a stylus pen [20] or conductive pad

[21]. However, human and environmental impedance causes non-uniform tactile feedback. An electrovibration display's touchscreen and the bare finger form an electrical circuit to generate electrostatic force [2]. In addition to signal rendering parameters, moisture [22], temperature [9], electrowetting [23], dielectric thickness [24], air gap [9], contact area [25], normal force [26], finger motion and contact by a second finger [4], and scanning speed [7], [10] affect tactile feedback. Kim et al. [19] employed current feedback to maintain electrovibration intensity over ambient impedances. This approach mitigated the risk of electrical shock risk and provided uniform tactile sensation irrespective of grounding or skin conditions.

B. Dynamics of tactile adaption

The human ability to adapt to changes extends to their sense of touch. It is well established that tactile perception and exploratory movements interact mutually. Specifically, the sensations derived from haptic feedback arise from the stimulatory input generated through these exploratory movements, which subsequently dictates the nature of the movements [11]. For instance, pressing is used for sensing compliance and high speeds for slippery tactile cues. Similarly, Callier et al. [12] observed that haptic experiences are essentially a byproduct of active movements and are significantly shaped by those movements. Vardar et al. [4] demonstrated through their work that the nuances of finger motion can significantly affect user perception.

For instance, electrovibration is more pronounced during interactions involving finger motion, as a moving finger experiences considerably larger fluctuating electrovibration forces than a stationary one [4]. This disparity is attributed to the variations in the resultant fingertip contact area and the air gap between the fingertip skin and the touchscreen surface during different types of interactions. Consequently, this alters the total electrical impedance in the resulting circuit between the two surfaces, leading to a change in the generated electrostatic attractive force [4]. Specifically, the measured electrical impedance for a stationary finger is almost 10 times lower than a moving finger, causing a decrease in the accrued effective voltage and resulting electrostatic force, making the stimulus difficult to perceive [4]. Additionally, real textures have surface properties that play a huge role in shaping human perception [11], compared to virtual sensations where the range of applied forces and scanning speeds mainly govern the quality and nature of human perception of tactile feedback.

C. Perceptual dimensions

The physical properties of a surface or texture can be identified very efficiently through haptic exploration [27]. Tactile perception involves using touch to perceive and understand material surfaces, often referred to as perceptual dimensions [28].

It is usually necessary to collect subjective data by employing psychophysical tests to determine the perceptual dimensions. The process involves gathering perceptual evaluations through the use of adjective labels on various materials. Subsequently, multivariate analysis is performed on the collected data to determine relevant perceptual dimensions [28]. Typically, three strategies are used. The semantic differential method involves participants ranking objects on a scale with opposing adjective pairs [29]. The similarity estimation method involves individuals rating paired material's perceived similarity [30]. Alternatively, the classification method involves users categorising items based on perceived similarity [11].

Okamoto et al. [28] identified five potential dimensions of tactile perception; namely macro and fine roughness, warmness, softness, and friction. The perceived texture sensations by the electrovibration technique are defined only in terms of smoothness/roughness and stickiness/slipperiness [8]. The electrovibration technology cannot yet generate softness and warmth perception.

1) Roughness perception: To quantify surface topography, also known as roughness, statistical techniques are used to measure vertical variations of a surface [31]. Generally, the combination of these parameters with other surface mechanical properties is perceived as roughness. Previous studies on real textures have shown that the proportions and spacing of tactile features, such as gratings, dots, and cones impact the perception of roughness [32]. According to Hollins et al. [33], roughness perception varies across microtextures (Inter-element spacing $\leq$ 0.2mm) and macrotextures (Inter-element spacing $\geq$ 0.2mm) due to vibrotactile and spatial cues respectively. Additional research has corroborated the notion that, perceived roughness is mostly influenced by gaps between the elements than the width of the elements at macro-texture level [34].

Additionally, Lederman & Klatzy found that speed has little impact on perceived texture roughness [34]. In another study, Cascio et al. [35] reported that temporal frequency (the ratio of finger speed to texture wavelength) impacts roughness perception. Later, Smith et al. [36] discovered a positive correlation between roughness perception and rate of change in lateral force. In their study, Tanaka et al. [11] found that individuals exhibit different strategies to perceive roughness textures. Their findings indicated that individuals exhibit a greater contact force variability with smooth stimuli compared to rough stimuli. Furthermore, Callier et al. [12] showed that roughness textures resulted in a significantly high percentage of linear movements of 77%, an average exploration time of 6.24 seconds, and a progressively widening range of scanning speeds for lateral motion.

The aforementioned studies provided us with a comprehensive understanding of roughness perception pertaining to real textures. However, given the increasing advancement of haptic devices and the diverse haptic rendering technologies, it is crucial to determine whether the perception of virtual textures aligns with that of real textures. Bau et al. [5] employed pure sinusoidal signals and found that low-frequency signals were perceived as rougher than high frequencies. Moreover, Isleyen et al. [32] conducted psychophysical tests on roughness perception for real and

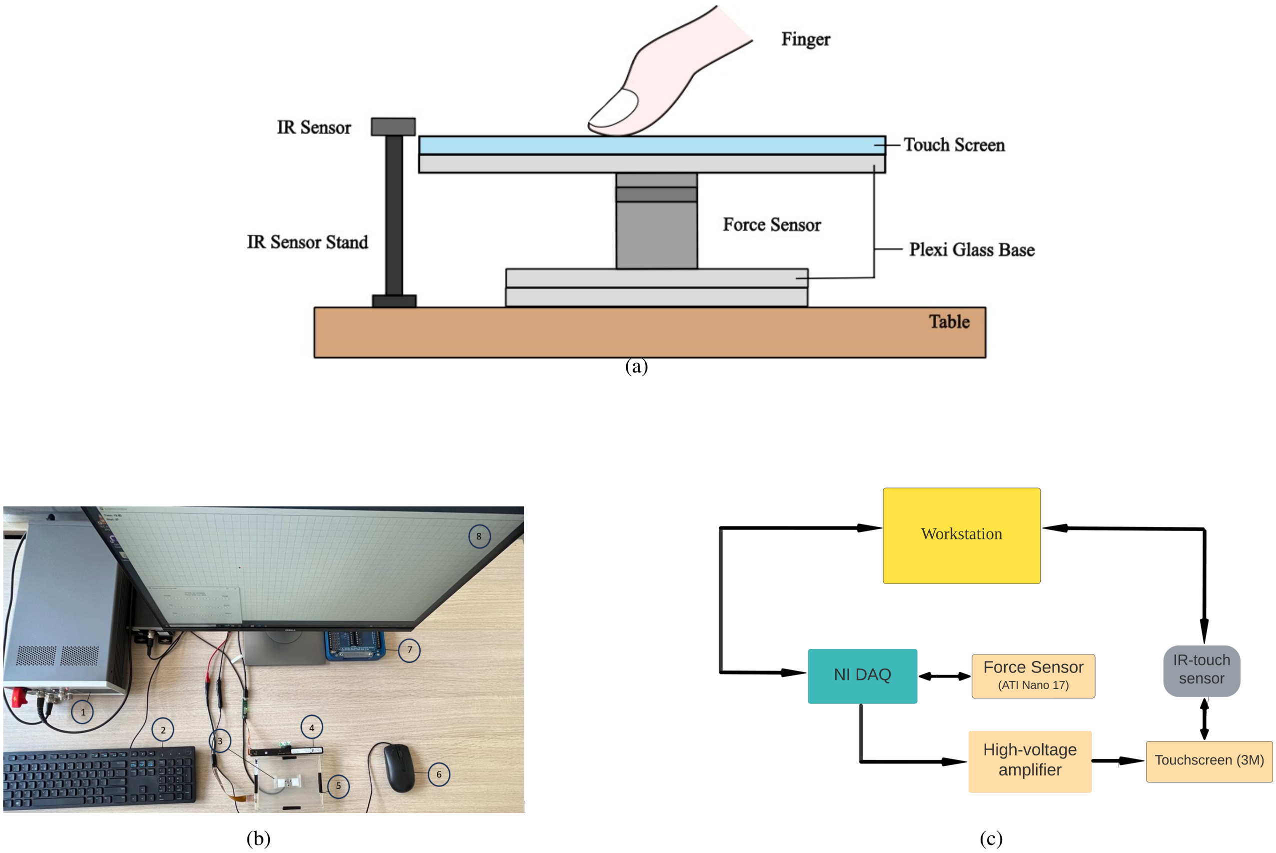


Fig. 2. Experimental set up used for the psychophysical experiment. a) Side-view of the experimental setup during finger touchscreen interaction. b) Set up top view containing (1) High-voltage amplifier, (2) Computer keyboard, (3) Touchscreen, (4) IR sensor, (5) Force sensor, (6) Computer mouse, (7) Ni-daq board, (8) LCD monitor displaying GUI. c) Block diagram illustrating signal workflow between the apparatus of the setup

virtual gratings, revealing that fingerpad penetration may explain perceived differences. Skin penetration enhances finger tangential forces on real gratings, whereas in virtual gratings without skin penetration, the spatial period was inversely proportional to the tangential forces, leading to a decrease in the magnitude [32].

It can be concluded that there is no single roughness parameter that correlates with perceived roughness. Instead, roughness is a multifaceted sensory experience impacted by characteristics such as signal intensity, asperity density, individual exploration behaviour, signal waveform, and friction between the surface and fingerpad [31].

2) Friction perception: Psychophysical term slipperiness refers to the perception of friction between a finger and a surface. Kuilenburg et al. [31] showed that the coefficient of friction between the finger and the surface is closely related to the perception of slipperiness. However, applying mild or moderate force during exploration results in a higher friction coefficient, because increasing normal forces increases tangential force while decreasing the coefficient of friction until a steady-state value [1]. Viscoelastic materials like fingertips frequently exhibit this behaviour. Additionally, Callier et al. [12] investigated the exploration of real textures in relation to slipperiness tasks. Their findings revealed that participants mostly engaged in linear movements (85% of exploration behaviour, average duration of 6.08 seconds) and lateral motion with very high scanning speed [12].

In order to perceive electrostatic-induced vibrations on a touch screen, the finger must be engaged in a sliding motion [4]. This is due to the fact that both lateral and normal forces contribute to the sense of friction. Friction coefficient is the ratio of resultant lateral force to applied normal force. Besides the average power of the vibration signal, slipperiness perception is characterised by this attribute [37]. Bau et al. [5] demonstrated that at low frequencies, increasing stimulus amplitude increases stickiness perception. Moreover, Sirin et al. [10] noticed a recurring stick-slip phenomenon at low velocities and a continuous sliding state without adhesion at high velocities. Additional factors affecting friction coefficient include surface roughness, moisture, fingerprints, age, and gender [2].

The exploratory movements associated with roughness and slipperiness textures differ likely due to the distinct neural mechanisms [31]. According to Weber et al. [38], roughness perception is governed by two mechanisms: spatial and temporal. The mechanoreceptors present in our fingertips and the human brain's quick processing capability of the texture-induced vibrations, render the finger scanning speed crucial for temporal perception. Conversely, the skin stretch and applied force observed while scanning are influential in determining the slipperiness perception [12].

III. Methodology

A. Psychophysical experiments

This experiment aimed to investigate the influence of different tactile rendering parameters on user exploratory behaviour and their perception during unconstrained exploration. Specifically, we analysed finger scanning speed, finger movement pattern (lateral sweeps and complex movements), and contact forces (lateral and applied normal forces) during unconstrained exploration. All participants were instructed to continuously explore artificial textures with their dominant index finger, maintaining contact with the screen, and subsequently evaluate the textures using predefined adjective scales. Preliminary tests were conducted to analyse a variety of signal-rendering parameters to deliver distinct stimuli to the individuals.

B. Subjects

Seven women and fourteen men with an average age of 24.6 years (standard deviation, SD: 1.59) participated in the psychophysical experiment. Only two participants were left-handed and none of the participants had previous or current visual or sensory-motor disabilities. The experimental device and procedures were approved by the Human Research Ethics Committee (Application number: 3274) at TU Delft. All participants gave written informed consent.

C. Experimental set-up

Participants sat in front of the touchscreen (6.71 inches, SCT3250, 3M Inc.) and an LCD monitor (fig. 2(b)). A force sensor (Nano17, ATI Inc.) was attached underneath the touchscreen to record the contact forces (lateral forces: Fx and Fy, normal force: Fz). These forces were sampled by a data acquisition card (PCIe-6323, NI) at 10 kHz. A touch module IR sensor (NNAMC1580PCEV, Neonode Inc.) was mounted on a 3D printed stand, which was positioned along one of the sides of the touchscreen. The finger position were recorded by integrating the IR sensor with a Pygame interface at 60 frames per second (FPS). The finger scanning speed, being the derivative of the finger position with respect to time was computed from this data. The finger movement pattern (lateral sweeps and complex movement) was obtained from finger position data using a custom Python code. Lateral sweep movement was characterised as an exploratory movement where the change in X-axis is more pronounced than the change in the Y-axis. Movements involving significant changes along both axes suggest a multi-directional, complex movement. For the physical support, we designed CAD models of the base support frame for the touchscreen and force sensor configuration using Solidworks (Dassault Systems Inc.) and cut out of a 3 mm thick PMMA Sheet.

The voltage signals applied to the touchscreen were first generated with the same data acquisition card and then amplified with a gain of 50x using a dual-channel high-voltage amplifier (9200A, Tabor Inc.). A side view (fig. 2(a)) and a comprehensive block diagram (fig. 2(c)) of the signal workflow between the apparatus of the setup are shown for reference. Electric adhesive tape was used to secure the wires, prevent potential electric shock, and avoid any current leakage. Participants also wore noise-cancellation headphones (TUNE760NC, JBL) with pink noise playing in the background to mask any auditory cues. Additionally, participants wore an anti-static strap on their non-dominant hand for grounding strategies.

The LCD monitor was used for interacting with the Pygame simulation and graphical user interface designed in MATLAB (refer to Appendix C). Participants provided their responses using a computer mouse and then proceeded to subsequent trials using a computer keyboard. The Python multiprocessing package was utilised to execute all the functionalities simultaneously.

D. Stimuli

We synthesised a range of virtual textures, each with unique features that can be manipulated both mathematically and perceptually, to facilitate a detailed analysis of sensory responses. This approach ensures precise control over selection and modification of the physical parameters [20]. While the ideal parameters for rendering distinct textures remain undetermined, previous studies have established that the frequency and amplitude of the sinusoidal textures as perceptual relevant features [39]. Friesen et al. [39] introduced irregularity as a third continuous texture feature, which quantitatively characterises the quality factor of a filter, subsequently influencing the width of the spectral content around the central frequency (f_0). This approach inspired our choice of frequency, amplitude, and irregularity of input voltage signals to generate diverse artificial textures on an electrovibration display.

A wide range of parameters were chosen to encompass a broad range of haptic sensations. We analysed our preliminary studies feedback and chose the centre frequency values as 40 Hz, 120 Hz, and 240 Hz. All three centre frequencies are well within the range of PC mechanoreceptor sensitivity and have demonstrated the capability to induce distinct haptic sensations. Shultz et al. [40] reported a rapid dielectric breakdown in the air gap at 150 V. In light of this, we opted to utilise amplitude values of 60 V, 80 V, and 120 V which also enabled us the flexibility to generate a wide range of perceivable distinctions.

The voltage signals were constructed from white noise that was made uniform in the range of [-1, +1] using the following infinite impulse response (IIR) filter:

$$H(z) = \frac{\frac{\sin w_0}{2Q} - \frac{\sin w_0}{2Q} z^{-2}}{\left(1 + \frac{\sin w_0}{2Q}\right) - (2\cos w_0)\, z^{-1} + \left(1 - \frac{\sin w_0}{2Q}\right) z^{-2}} \quad (1)$$

where the Q-factor and w_0 are calculated as:

$$Q = \frac{1}{R} \quad (2)$$

$$w_0 = \frac{2\pi f_0}{f_s}. \quad (3)$$

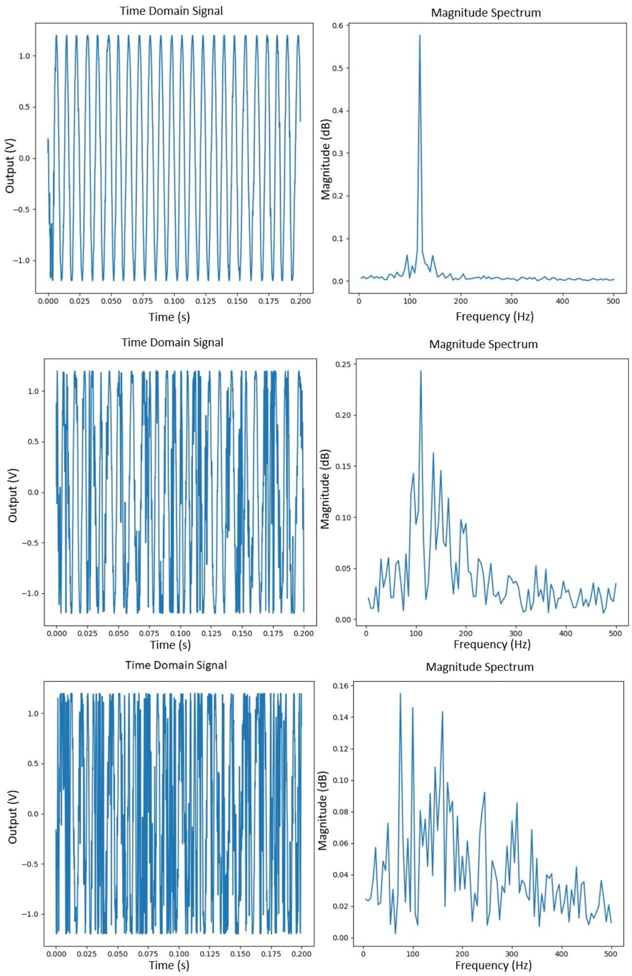


Fig. 3. Time domain signals and their magnitude spectra (computed using the Fast Fourier Transform (FFT) method in the time interval 0 to 0.2 seconds) for three different irregularity values used in our study, all with 120 Hz center frequency and pre-gained amplitude of 1.2 V

Based on equations 2 and 3, the irregularity value, denoted as R, exhibits an inverse relationship with the Q-factor and has implications for the frequency characteristics of the constructed voltage signals. The irregularity value (R) serves as a measure of the complexity, noise, and irregularity present in the signal that influences the creation and perception of various artificial textures. The Q-factor is associated with filtering of white noise signals to create distinct textures by modulating irregularity. Here, f_0 represents the central frequency of the signal, while f_s corresponds to the sampling frequency, which was set to 10 kHz. To maintain a consistent range of the filtered signals, it was necessary to address the potential issue of low-frequency amplitude fluctuations that may arise from narrower band filtering [39]. To mitigate this, the envelope of each filtered signal was computed using the Hilbert transform (from the Scipy Python package) and subsequently, each filtered signal was divided by its envelope. Finally, the normalised filtered signal is scaled using the amplitude value.

The experiment utilised irregularity values (R) of 0.0001, 0.34, and 1.67 to elicit various sensory perceptions. These values bear a close resemblance to those employed by the studies [20], [39]. As the irregularity value decreases, the signals exhibit a greater affinity to a simple sinusoidal wave. Conversely, an increase in the irregularity value introduces additional spectral noise to an established pattern such as a sinusoidal wave [39] (fig. 3). The parameter values used in our study are listed in Table I. The combination of all the parameters (3x3x3) yielded 27 different artificial textures.

TABLE I
PARAMETER VALUES OF THE SIGNAL PARAMETERS

Parameters	Values
Centre frequency (Hz)	40, 120, 240
Amplitude (V)	60, 80, 120
Irregularity	0.0001, 0.34, 1.67

E. Adjectives

Based on the preliminary investigations and review study on electrovibration [1], six sensory adjectives were selected and grouped into three pairs representing polarising ends of specific tactile sensations. (see Table II).

TABLE II
SET OF ADJECTIVES USED IN THE EXPERIMENT

Adjective pairs
Smooth Rough
Flat Bumpy
Sticky Slippery

F. Experimental Procedure

The experiment comprised two stages: a training session and the main experiment, which was divided into two separate sessions. All the participants were instructed to wash and dry their hands before the start of the experiment. Next, they sat in a comfortable position in front of the experimental setup. Before the start of each experiment, the electrovibration display was cleaned with isopropyl alcohol.

Each participant utilised their dominant hand's index finger to freely explore the artificial textures while engaging with the graphical user interface, which tracked their finger as a red dot and provided real-time visual feedback to indicate their finger's position. The training session had ten trials, each lasting ten seconds, allowing them to familiarise and ease into the experimental setup and procedure. During the training session, each participant received a brief presentation that comprised an overview of the technology, structure of experiment, and clear instructions on procedure. The slides from the presentation can be found in the Appendix C.

The main experiment included 27 trials per session, with an inter-session break for 5-10 minutes, culminating in a total of 54 trials. The duration of each trial in the main experiment was 20 seconds. The order of the trials were randomised for every session and participant. Before the commencement of the main experiment, the experimenter entered the participant's ID. The participant then pressed the start button. This action prompted a 2-second waiting message, informing the onset of the experiment. Subsequently, they started freely exploring the electrovibration display for the specified time duration while their finger position and contact forces data were recorded continuously. The trial conclusion was marked by the cessation of the red dot and the simultaneous termination of a timer clock in the GUI. Additionally, an automated auditory message was delivered to indicate the end of the trial.

After this, the participants rated the artificial textures on a free 7-point semantic differential scale for all three pairs of sensory adjectives. Each pair was placed on polarising ends of the scale. The participants were required to press the submit button to log their ratings for that trial. Once they were ready, they pressed "N" on the computer keyboard and a beep sound cue indicated the advancement to the next trial immediately. The duration of the entire experiment was around 45-60 minutes. Each participant was asked two subjective feedback questions at the end of the experiment. The primary data for analysis consisted of the measured finger position, derived finger scanning speed, and measured contact forces for all trials, as well as the 54 x 3 = 162 sensory adjective pairs ratings obtained from each participant (refer to Appendix C).

G. Data analysis

1) Data preprocessing: The inherent noise in the touch module IR sensor or any fluctuations in the Pygame interface might result in rapid variations in the speed data. To mitigate this issue in real-time, a moving average filter was applied to the raw speed data during the experiment, which served as a low-pass filter with a cut-off frequency of 6 Hz. The filter was applied to the derived finger speed rather than measured finger position to accurately capture the finger movement pattern. Applying it directly to finger position data could also potentially lead to over-smoothening of the speed data. Additionally, the difference in the root mean square (RMS) value of the average raw speed and the average filtered speed was around 0.198, indicating a mild filtering effect. The Signal-to-noise (SNR_{dB}) ratio was 15.61, suggesting that the power of the filtered speed was over 35 times that of the noise. This attested to the effectiveness and appropriateness of performing a real-time filtering process while still retaining the fundamental trends in the speed data. Interestingly, the denoised speed (orange line) in the fig. 4 surpasses the raw speed (blue line) at few instances (in the 5.7 to 6.1s interval). This is most likely due to the moving average filter's window size and data gap, which incorporates preceding higher values of raw speed data and raises the filtered data.

The initial two seconds and the last four seconds of all the finger position, scanning speed and contact forces data were trimmed out from all the trials to have a constant exploration time across all participants. The derived raw scanning speed data points were interpolated to match the measured raw applied normal force data points, employed

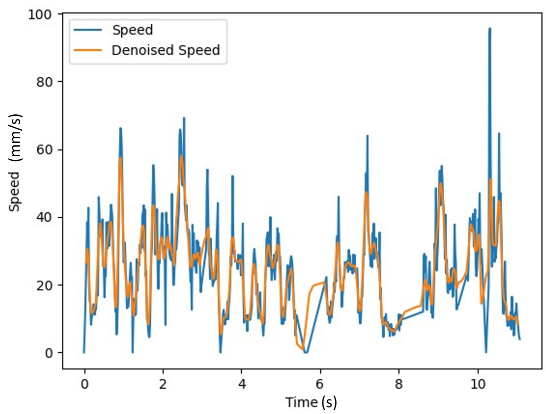


Fig. 4. Illustration showing both raw speed and filtered (denoised) speed (in mm/s) over a 10-second duration taken during preliminary experiments

across all trials by all participants to develop a heat map (fig. 7). We developed another heat map (fig. 6) by plotting the raw finger position coordinates across all trials for all participants. Multiple metrics, including the mean and maximum values for each trial, were considered to characterise finger scanning speed and contact forces. Due to their nature as time-varying continuous variables, we chose the mean values of the trimmed data for further analysis (refer to Appendix D and Table III).

2) Statistical analysis: Friedman test, a non-parametric statistical test alternative to repeated measures ANOVA was utilised to study the significance of different tactile rendering parameters on derived user's finger scanning speed, measured applied normal force, and measured finger position. Additionally, we also studied their significance on sensory adjective ratings provided by the users with the Friedman test. It was followed by a post-hoc Wilcoxon signed-rank test with Bonferroni correction. A Bonferroni correction is a commonly used method to prevent Type-I errors (false positives) because of multiple comparisons. In addition to evaluating the statistical significance between the variables, we utilised Kendall's coefficient of concordance as an effect size measure. The correlation between the sensory adjective ratings with mean scanning speed, coefficient of friction, normalised RMS of rate of change of lateral force were also analysed for all trials (n=1134, 21x54) (refer to Section II-C). It is important to note that the lateral force utilised here is the resultant of lateral forces (Fx and Fy).

TABLE III
LIST OF INDEPENDENT AND DEPENDENT PARAMETERS

Independent Parameters	Dependent Parameters
Frequency	Finger scanning speed (mean) (derived from finger position)
Amplitude	Finger movement pattern (raw) (obtained from finger position)
Irregularity	Contact forces (mean) (lateral force and applied normal force) Sensory adjective ratings (mean)

IV. Results

A. Effect of tactile rendering parameters on user exploratory behaviour

To assess the effect of different tactile rendering parameters on user exploratory behaviour, we employed the Friedman test, conducting it individually on the mean scanning speed and mean applied normal force calculated over all trials for all 21 participants. The analysis involved a 21x3 matrix, where the 21 instances in this matrix contains the mean measurements of speed and normal force of all participants and the 3 corresponds to the different signal parameters. The results indicated a statistical significant effect of signal parameters on scanning speed, χ^2 = 73.55, $p < 0.0001$, paired with a Kendall's W value of 0.24. The W value suggests a small effect size, reflected by the the high individual differences in mean speeds observed across all participants (see Table IV and fig.5(a)).

Moreover, the post-hoc analysis revealed statistical significant differences between 40 and 240 Hz frequency and across all amplitude levels ($p < 0.01$). There were no significant differences across different levels of irregularity. Additionally, signal rendering parameters did not impact the applied normal force, as evidenced by ($p > 0.05$). This finding was further backed by a very low Kendall's W value of 0.002. Moreover, our results indicated a weak negative correlation of (r = -0.137) between finger scanning speed and applied normal force.

The overall average of mean speed across all participants showed a very slight increase as the signal frequency increased. Conversely, the overall average of mean speed decreased with an increase in amplitude (fig. 5(a)). To gain a better understanding of whether users adjusted their scanning speed based on different signal parameters, we plotted the mean finger scanning speed against time for each amplitude at every timestamp for all participants, as shown in fig. 5(b).

We further analysed the finger movement pattern using measured raw finger position data for each trail of all participants across different signal parameters using Friedman test. The results showed no statistical significant influence of signal parameters on the chosen finger movement pattern (lateral sweeps & complex movements), with the χ^2 values being 1.06, 1.66, and 0.48 for frequency, amplitude, and irregularity respectively with (all *p-value* $>$ 0.05). The results across all trials for all participants revealed that 62% of their movements were lateral sweeps and 38% were complex movements. No stationary movements were recorded since the participants were instructed to keep their fingers sliding. We plotted a heatmap (fig: 6) to illustrate the finger position of all the participants under all the different conditions. The mean finger position is found to be (7.39, 5.29) with a SD of 2.81 and 2.17 cm in X and Y directions, respectively.

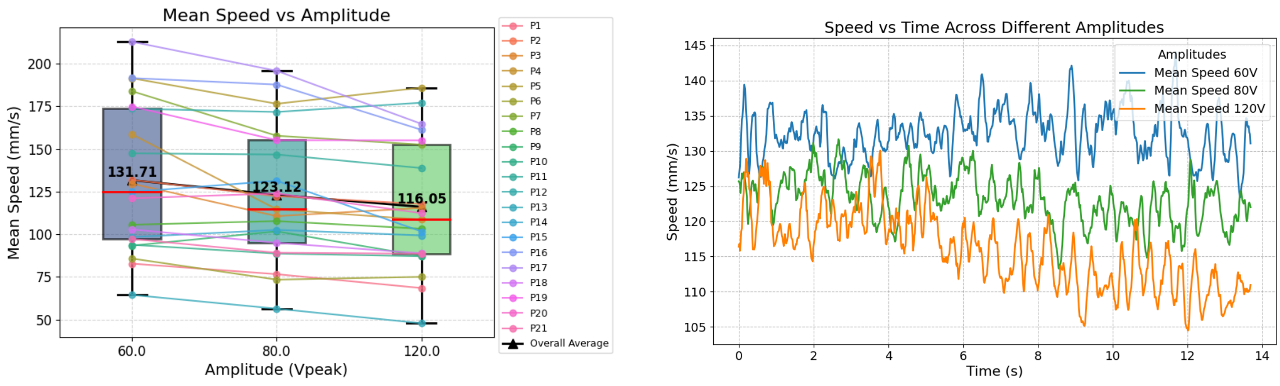
Lastly, we superimposed the derived raw interpolated speed data with the normal force data for all trials and participants to pinpoint a potential predominant tendency in terms of finger scanning speed and applied normal force (fig. 7). Our findings suggested that there is no such predominant tendency, as all the participants exhibited a high variability in scanning speed and applied normal force during unconstrained exploration. Additionally, we examined the 10th and 90th percentile of this data to understand the range and variability of the data set. Scanning speed; 10th Percentile: 38.21 mm/s, 90th Percentile: 221.04 mm/s and applied normal force; 10th Percentile: 0.13 N, 90th Percentile: 0.99 N.

B. Effect of tactile rendering parameters on user perception during unconstrained exploration

To study the impact of tactile rendering parameters on user perception during unconstrained exploration, the Friedman test was applied to analyse adjective ratings provided by the participants. The analysis utilised a 21 x 3 matrix, where 21 encompasses the mean value of the different pairs of sensory adjective ratings for all trials across all participants and 3 corresponds to the different signal parameters. The test revealed a statistical significant effect of all signal parameters on user perception ($p < 0.001$). To further understand these effects, the post-hoc analysis conducted, indicated significant differences across multiple levels of different signal parameters on user perception. The subsections below provide comprehensive findings related to tactile rendering parameters on different virtual texture perceptions. In Table IV, we present the mean and standard deviation of ratings for different sensory adjective pairs across all trials and participants, associated to the 27 different signals used in our study. Lastly, an overview of all the findings are presented in Table V.

1) Roughness perception: The results showed statistical significant effects of frequency, amplitude, and irregularity on roughness perception with respective χ^2 values of 17.48, 172.47, and 18.38 ($p < 0.05$). For amplitude, Kendall's W value of 0.27 indicated low to moderate effect size which suggests that while there is some association between amplitude and perceived roughness, it is not strong. In contrast, the effect size for frequency and irregularity were weaker. Subsequent post-hoc analysis revealed these specific significant differences: between 120 and 40 Hz, 120 and 240 Hz for frequency and between 1.67 and 0.0001, 0.34 and 0.0001 for irregularity. The analysis indicated a highly significant difference across all levels of amplitude ($p < 0.01$) (see Table IV and Appendix B).

Additionally, we examined the effect of scanning speed on roughness perception. Our results revealed a moderate negative correlation (r = - 0.31) between the overall speed and perceived roughness (fig. 8(a)). This finding may imply that scanning speed increases with an increase in the perception of smoothness textures or vice-versa. Additionally, we found a strong positive correlation (r = 0.53) between the rate of change of lateral force and roughness rating (fig. 9(a)). Lastly, the coefficient of friction exhibited a very weak complex behaviour with roughness perception. It increased up to a certain threshold, after which it decreased until reaching almost a steady state.



(a) (b)

Fig. 5. (a) Boxplot depicting finger scanning speed with amplitude, shows the value of mean speed for each participant relative to amplitude and the overall average of the mean speed across all participants (b) depicts the mean finger speed over a 14-second duration, with data recorded at 60 FPS across different amplitude. Each point represents the mean speed calculated from 378 data values (21 participants, 18 trials corresponding to each amplitude level) at each timestamp, interconnected to display the speed trend

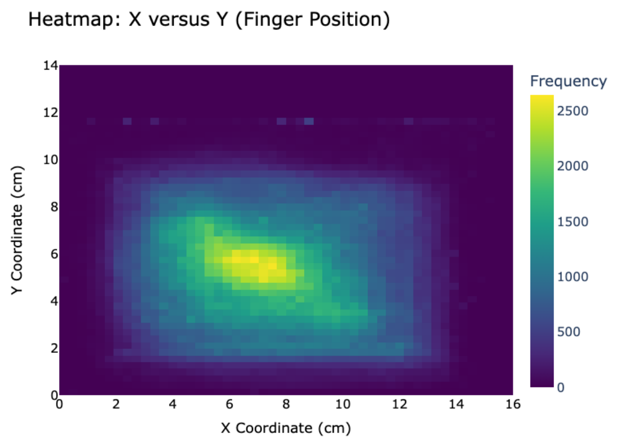


Fig. 6. Heatmap of the distribution of data points (1088873 each) in the X-Y plane, derived from a 2D histogram with 50 bins on each axis; 0.32 cm bin size for X-axis (0-16 cm), and 0.28 cm for Y-axis (0-14 cm)

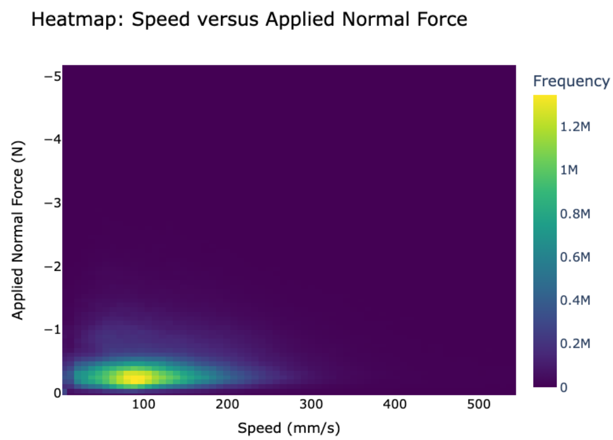


Fig. 7. Heatmap illustrating the distribution of interpolated data points (175870201 each) in the Speed vs Applied Normal Force plane, with the color intensity indicating frequency of occurrences. The Speed axis is divided into 200 bins of 8.46 mm/s width, while the Applied Normal Force axis has 200 bins each of 0.07 N width. Negative force indicates the vertically downward direction

2) Bumpiness perception: Similar to roughness perception, all the signal parameters showed a statistical significant effect on bumpiness perception ($p < 0.05$). Frequency and amplitude showed a highly significant effect compared to irregularity with respective χ^2 values 68.2, 87.9, and 11.02. Kendall's W showed weak to moderate effect size among participants for frequency and amplitude but negligible effect size for irregularity. Moreover, the post-hoc analysis indicated a significant difference across all levels of frequency and amplitude in their effect on bumpiness perception. A significant difference was also found between 1.67 and 0.34 irregularity values($p < 0.01$) (see Table IV and Appendix B).

Moreover, our results indicated a moderate negative correlation (r = - 0.32) between the overall speed and perceived bumpiness (fig. 8(b)), suggesting that increased scanning speed is associated with an increase in flatness perception or vice-versa. Our analysis also suggested a robust weak correlation (r = 0.29) between the rate of change in lateral force and bumpiness perception. It remained stable until a threshold and increased beyond that point (fig. 9(b)). The coefficient of friction did not exhibit any correlation with bumpiness perception.

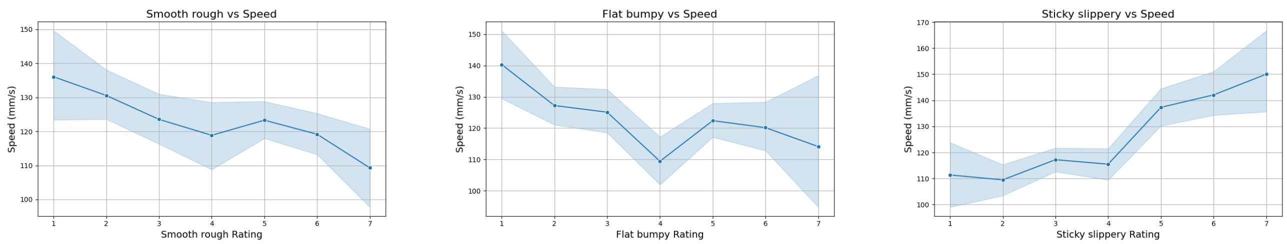
3) Slipperiness perception: Test results showed statistical significant effects of signal parameters on slipperiness perception($p < 0.05$). The χ^2 values for frequency, amplitude, and irregularity were 12.6, 86.14, and 17.2 respectively. A similar trend was also observed in the Kendall's W value for the three signal parameters, implying low to moderate effect size among participants for amplitude (W = 0.21) but very low effect size for frequency and irregularity. Subsequent post-hoc analysis revealed significant differences between frequencies 120 and 240 Hz and irregularities 0.34 and 0.0001. As expected, the analysis indicated a highly significant difference across all levels of amplitude($p < 0.01$). (see Table IV and Appendix B).

TABLE IV
MEAN AND STANDARD DEVIATION (MEAN, SD) OF SENSORY ADJECTIVE RATINGS AND SCANNING SPEED FOR DIFFERENT SIGNALS STUDIED (ACROSS 1134 TOTAL DATA POINTS), WITH MARKED ROWS HIGHLIGHTING THE EFFECT OF AMPLITUDE ON USER PERCEPTION AT DIFFERENT FREQUENCY AND IRREGULARITY LEVELS

Frequency (Hz)	Amplitude (V)	Irregularity	Smooth Rough	Flat Bumpy	Sticky Slippery	Speed (mm/s)
40.0	60.0	0.0001	(2.71, 1.50)	(4.02, 1.60)	(4.71, 1.52)	(124.90, 43.72)
40.0	60.0	0.34	(3.41, 1.45)	(3.60, 1.73)	(4.12, 1.45)	(128.47, 50.41)
40.0	60.0	1.67	(3.69, 1.65)	(2.88, 1.29)	(4.07, 1.66)	(127.45, 58.70)
40.0	80.0	0.0001	(3.29, 1.64)	(4.45, 1.71)	(4.36, 1.65)	(123.99, 48.27)
40.0	80.0	0.34	(4.17, 1.53)	(4.43, 1.56)	(3.86, 1.41)	(120.31, 50.13)
40.0	80.0	1.67	(4.76, 1.41)	(4.14, 1.51)	(3.88, 1.61)	(114.50, 42.54)
40.0	120.0	0.0001	(3.81, 1.69)	(4.91, 1.69)	(3.88, 1.60)	(122.47, 46.97)
40.0	120.0	0.34	(4.71, 1.52)	(4.91, 1.59)	(2.95, 1.31)	(112.30, 45.50)
40.0	120.0	1.67	(5.50, 0.94)	(4.81, 1.42)	(3.12, 1.23)	(114.24, 43.93)
120.0	60.0	0.0001	(3.86, 1.46)	(3.38, 1.61)	(4.19, 1.58)	(127.61, 55.24)
120.0	60.0	0.34	(3.76, 1.45)	(3.29, 1.37)	(3.60, 1.31)	(125.73, 42.82)
120.0	60.0	1.67	(3.5, 1.50)	(2.95, 1.45)	(4.48, 1.44)	(138.34, 54.09)
120.0	80.0	0.0001	(4.55, 1.45)	(3.64, 1.79)	(3.81, 1.58)	(123.57, 45.88)
120.0	80.0	0.34	(4.19, 1.64)	(3.64, 1.48)	(3.57, 1.29)	(126.09, 41.70)
120.0	80.0	1.67	(4.31, 1.39)	(3.21, 1.49)	(3.64, 1.50)	(122.83, 42.76)
120.0	120.0	0.0001	(5.10, 1.43)	(3.45, 1.66)	(3.19, 1.29)	(115.29, 46.93)
120.0	120.0	0.34	(5.21, 1.22)	(4.19, 1.44)	(2.98, 1.41)	(118.76, 51.44)
120.0	120.0	1.67	(5.05, 1.50)	(4.19, 1.64)	(3.45, 1.42)	(117.29, 49.97)
240.0	60.0	0.0001	(3.0, 1.58)	(2.69, 1.57)	(4.91, 1.28)	(136.07, 57.61)
240.0	60.0	0.34	(3.36, 1.61)	(3.10, 1.45)	(4.62, 1.55)	(133.33, 58.20)
240.0	60.0	1.67	(2.93, 1.58)	(2.19, 0.94)	(4.69, 1.66)	(143.47, 60.06)
240.0	80.0	0.0001	(3.67, 1.66)	(3.41, 1.25)	(4.00, 1.51)	(118.89, 43.32)
240.0	80.0	0.34	(4.21, 1.26)	(3.43, 1.61)	(3.88, 1.47)	(125.58, 58.65)
240.0	80.0	1.67	(4.14, 1.65)	(2.95, 1.34)	(3.83, 1.38)	(132.37, 56.32)
240.0	120.0	0.0001	(4.33, 1.60)	(3.41, 1.53)	(3.41, 1.48)	(115.80, 42.55)
240.0	120.0	0.34	(4.88, 1.38)	(4.12, 1.73)	(3.21, 1.47)	(110.73, 45.00)
240.0	120.0	1.67	(4.86, 1.46)	(3.79, 1.69)	(3.21, 1.35)	(117.62, 44.94)

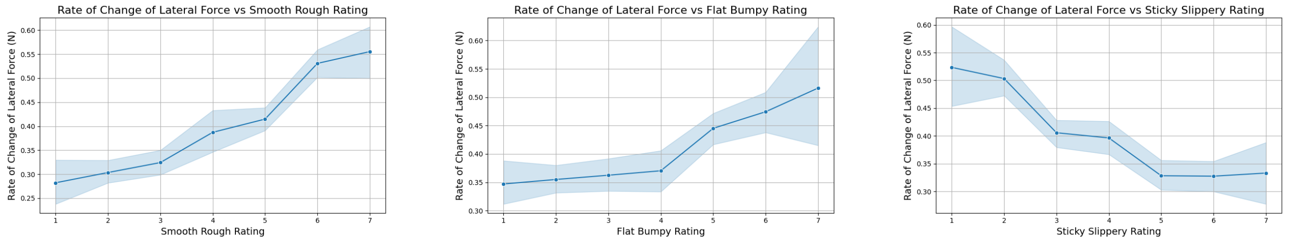
TABLE V
OVERVIEW OF THE RESULTS FROM SECTION IV-B

Tactile Dimensions/Parameters	Frequency	Amplitude	Irregularity	Scanning speed	Lateral force rate	Coefficient of friction
Roughness	χ^2 = 17.48, $p < 0.05$, Significant effect	χ^2 = 172.47, $p < 0.05$, Highly Significant effect	χ^2 = 18.38, $p < 0.05$, Significant effect	r = - 0.31, Moderate negative correlation	r = 0.53, Strong positive correlation	Weak/Complex positive correlation
Bumpiness	χ^2 = 68.2, $p < 0.05$, Highly Significant effect	χ^2 = 87.9, $p < 0.05$, Highly Significant effect	χ^2 = 11.02, $p < 0.05$, Significant effect	r = - 0.32, Moderate negative correlation	r = 0.29, Weak positive correlation	No Correlation
Slipperiness	χ^2 = 12.6, $p < 0.05$, Significant effect	χ^2 = 86.14, $p < 0.05$, Highly Significant effect	χ^2 = 17.2, $p < 0.05$, Significant effect	r = 0.39, Moderate positive correlation	r = - 0.38, Moderate negative correlation	Weak/Complex positive correlation



(a) (b) (c)

Fig. 8. Line plots illustrating the relationship between mean scanning speed with different sensory adjective rating levels with their respective confidence intervals



(a) (b) (c)

Fig. 9. Correlation between normalised RMS of the rate of change of lateral force as a function of different tactile perception ratings, paired with their corresponding confidence interval

Apart from signal rendering parameters, our results also showed that an increase in speed is associated with the perception of slipperiness or vice-versa, a conclusion further substantiated by a moderate positive correlation (r = 0.39) between them (fig. 8(c)). Moreover, the rate of change of lateral force exhibited a moderate negative, yet complex, correlation (r = -0.38) with the slipperiness rating (fig. 9(c)). Lastly, our results suggested that the coefficient of friction initially increases in tandem with the perceived slipperiness up to a threshold and then exhibits a minor decline.

V. Discussion

In this study, we examined the existence of a predominant tendency among users during unconstrained exploration of artificial textures generated using electrovibration technology. We focused on characterising the exploratory behaviour in terms of three key variables: finger scanning speed, finger movement pattern, and applied normal force. These variables are critical because the motion of the finger is paramount in perceiving electrovibration stimuli [4]. Moreover, finger scanning speed and applied normal force are the foundational elements that contribute to the development of the contact mechanism during finger-touchscreen interactions. Additionally, prior research indicated the mutual nature of tactile perception, which enables the users to adjust their finger scanning speed and normal forces when engaging with real textures [11]. We extended this investigation to artificial textures by looking at the two aforementioned aspects.

A. Effect of tactile rendering parameters on user exploratory behaviour

Our results suggested that the signal rendering parameters influences the user's exploratory behaviour slightly during finger motion. Despite the applied normal force and finger movement pattern remaining largely consistent, the scanning speed exerted by the participants was weakly affected by the signal amplitude. However, there were large individual differences observed (fig. 5(a)), indicating unique way of exploration among participants. One possible explanation for the consistent applied normal force and finger movement pattern could be the participant's tendency to utilise light touch exploration on a flat touchscreen surface, possibly influenced by their visual perception [41]. Moreover, Smith et al. [42] found that participants maintained a relatively constant normal force (0.2 - 1.0N) in the subjective evaluation of smooth surface friction which somewhat aligns with the majority range (90th percentile) of the normal force we observed (0.07 - 0.99N). Additionally, Tanaka et al. [11] reported a lower average applied force for rougher stimuli than for smoother ones. The probable reason behind these discrepancies may be the absence of fingerpad penetration on flat touchscreen surfaces as opposed to real textures [32].

Specifically, it was noted that the overall average of the mean scanning speed increased slightly with frequency. This observation aligned with findings that indicated, low-frequency signals are perceived as rougher [5], [7]. Hence, participants tended to increase their finger scanning speed for high-frequency, smoother signals. This corroborated with previous observations made for real textures [11], [12]. Alternatively, the overall average of the mean scanning speed reduced as the amplitude of the signal increased, likely due to its impact on roughness perception, as a result of irregularity inclusion. The participants seemed to be cognisant of subtle changes more clearly as the amplitude intensified and subsequently reduced their scanning speed.

Interestingly, we observed no significant impact of irregularity on scanning speed. The lack of effect might be due to high scanning speeds limiting the sensory system from fully processing the nuanced details within a short duration. Otherwise, it could be due to the equivalent energy distribution over all frequency components with changing irregularities (see Appendix A). Contrary to the findings of [12], our results showed that there were no changes in finger movement patterns employed by the participants across various signal parameters. This inconsistency may arise from the flat touchscreen's lack of surface properties in combination with the visual perception compared to real textures.

The mean speed vs time graph (fig. 5(b)) for amplitude revealed a pattern common across all the participants. They maintained the same scanning speed initially but varied them as they became more familiar with the signal characteristics, indicating potential adaptive behaviour. Additionally, our data suggested that the normal force data is affected by scanning speed, in line with previous study [7]. This might explain the utilisation of low normal forces (negatively correlated with speed) by the participants, potentially to improve their perception abilities.

B. Effect of tactile rendering parameters on user perception during unconstrained exploration

Our findings indicated that the tactile rendering parameters significantly impact user perception during unconstrained exploration. The perception of roughness and slipperiness was evaluated with the perception of bumpiness, which is a common tactile dimension examined in previous studies [1], [5]. The amplitude of the signal stood out against all other parameters and significantly impacted the user perception at different levels. This could be understood from the fact that at such high scanning speeds, the intensity of the signal was the primary source for shaping the user's perception. The following subsections will provide a comprehensive discussion of our findings related to different perceptual dimensions.

1) Roughness perception: The mean roughness perception rating positively correlated with amplitude. A similar trend was found with irregularity, reaching a plateau at 0.34 and 1.67. This behaviour may stem from a balanced frequency distribution with the increase in irregularity. The results are largely consistent with [20], although it is worth noting that they employed an indirect contact interaction using a stylus pen instead of a bare finger. Additionally, lower-frequency signals were perceived as rougher consistent with earlier research [5], [7]. Interestingly, the roughness perception spiked for 120 Hz signal. The plausible reason is that nearly 1/3rd of our generated signals were almost pure sinusoidal waves (with irregularity of 0.0001). The electrostatic force frequency, being double the actuated signal frequency (at 240 Hz) [4], falls well within the high human sensitivity range. Hence, enhancing the user perception (see Appendix A).

Moreover, roughness perception was negatively correlated with scanning speed. The likely reason is the usage of lower scanning speeds for rougher textures because of aversiveness, aligning with previous findings on real textures [11], [12]. Our findings correlate with earlier research [32], [36], which showed that the root mean square (RMS) of normalised lateral force is a better metric of perceived roughness than its magnitude. This is because it records the dynamical changes in artificial texture characteristics. However, the reported correlation values differed, possibly due to texture properties, experimental procedures, and participants. Finally, friction coefficient exhibited a non-linear relationship with roughness perception, aligning with prior research [36]. Non-linearities were especially evident at low contact forces, as fingertip skin is highly compliant.

2) Bumpiness perception: Our results revealed that the mean bumpiness perception positively correlated with amplitude and negatively with frequency, aligning with previous findings [5]. The amplitude represents the texture height, [1] and probably contributed to the bumpiness perception. Conversely, the perception of flatness increased with frequency. The majority of the participants reported difficulty in distinguishing between rough & bumpy and smooth & flat textures. This observation is supported by a moderate positive correlation between the two tactile dimensions. However, further investigation is needed to capture the individual characteristics of each texture.

Moreover, the robust behaviour between the rate of change in lateral force and bumpiness perception suggests that the lateral force remained constant for flat textures but spiked up for bumpy ones. This behaviour can be understood from the increased resistance during finger motion on bumpy surfaces. This also underlines the different interplay of contact mechanics, as the real area could be different from the apparent area of contact for such surfaces.

3) Slipperiness perception: Our study revealed that the mean slipperiness perception ratings were negatively correlated with amplitude. An increase in amplitude elevated the perception of stickiness, consistent with earlier research [5]. The probable reason is the increase in friction between the skin and the touchscreen surface at high-intensity signals, often governed by adhesion at low contact forces [1]. However, Sirin et al. [10] noticed a continuous sliding state at higher speeds without adhesion. Moreover, contrary to previous findings [5], our results revealed no noticeable relationship between frequency and slipperiness perception. These discrepancies may arise from the usage of different signals and utilisation of unconstrained exploration.

Moreover, finger scanning speed was positively correlated with slipperiness perception, aligning with previous research on real textures [12]. Higher speeds induce a continuous sliding state, thus enhancing the slipperiness perception [10]. The complex behaviour observed between the rate of change in lateral force with slipperiness perception may be attributed to the stick-slip phenomenon at lower speeds for sticky textures. This might lead to a higher variation in lateral forces. Importantly, participants associated rough and bumpy textures with stickiness, confirmed by a moderate negative correlation between them. Lastly, the intricate relationship between the coefficient of friction and slipperiness perception might be impacted by high speeds and individual variability.

This study pinpointed the effect of different tactile rendering parameters on user perception during unconstrained exploration. It is important to highlight a potential element of reverse causality in the correlation between finger scanning speed and perception of different perceptual dimensions. For instance, if a user experiences low friction forces due to a slippery surface, it could automatically lead to higher scanning speeds, indicating that the perception of tactile stimuli could, in turn, influence the exploratory behaviour as well. Moreover, some disparities were observed across other parameters when compared to previous studies. These inconsistencies warrant further investigation.

C. Variability

Despite the consistent experimental conditions for all participants, high variations in measured parameters were observed. These variations likely attributed to the unconstrained exploration and individual variability, evidenced by the significant standard deviation in the finger scanning speed presented in Table IV. Additional factors such as skin properties, human psychophysical sensitivity, fingerpad sweat, finger size, gender, and body temperature may lead to such disparities [2], [22], [43]. For instance, 57% of female participants used scanning speeds higher than the mean speed, compared to only 33% of male participants.

D. Performance and Safety

To examine both device performance and participant safety during the experiment, we collected their subjective feedback through two questions. The average rating for the overall quality of the virtual textures experienced during the experiment was 3.81 out of 5 across all participants, indicating a satisfactory device performance. Finally, none of the participants reported any discomfort or pain during the experiment, validating the safe usage of the device.

E. Limitations and Future work

During the training phase of the experiment, participants were not informed about the specific sensations associated with the artificial texture sensations they encountered to avoid any bias in the main experiment. Participants reported confusion distinguishing between the sensory adjectives (Smooth-Rough and Flat-Bumpy). Moreover, the peripheral region of the touchscreen was available for exploration which offered intensified sensations possibly attributed to the collection of dust at the corners or the electrical connections situated at the edges. This might have affected the participant's perception in few trials. However, this issue was only reported by two participants. In future research, it is necessary to address these issues alongside the potential discrepancies outlined in Section V.

Future studies can explore the signal characteristics during active exploration over electrovibration display. Similar work was conducted either in a controlled environment with a robotic arm [37] or on real textures [44]. A comprehensive analysis in this area can provide critical insights regarding the correlation between human tactile perception and signal properties. Additionally, the contact area and fingerpad moisture were not recorded in our study which significantly affects human tactile perception [4], [22]. Incorporating high-resolution imaging methods of finger-touchscreen contact and moisture level sensors can offset these limitations. Lastly, our results hinted at a potential interaction effect of finger scanning speed and applied normal force with signal parameters on user perception. This presents an open research question for future studies.

VI. Conclusion

This study aimed to understand the effect of tactile rendering parameters on user exploratory behaviour and perception during unconstrained exploration. Specifically, we sought to identify the existence of a predominant tendency, a behaviour that might balance the human perception capabilities with the characteristics of electrovibration technology, with minimal trade-off during unconstrained exploration. For this purpose, we conducted a psychophysical experiment where subjects were allowed to explore the actuated electrovibration display freely and rate artificial textures. Based on our findings we can conclude that:

- To the best of our knowledge, this is the first electrovibration study where subject's haptic exploration was not controlled to examine their exploratory behaviour and tactile perception during haptic exploration.
- The freedom given to subjects in exploring the surface resulted in high variability, suggesting that each subject has a unique way of exploration.
- Signal intensity was found to be the major contributor in shaping user perception during unconstrained exploration. Additionally, increase in signal amplitude caused a consistently lower finger scanning speed among users. However, individual differences were still considerably large, so in practical terms the effect seems small to moderate (even though it is statistically significant).
- Although a *predominant tendency* of exploring the artificial textures across the actuated electrovibration display was not identified, we observed slight adaptability through a realignment of finger scanning speed.
- The rate of change in lateral force is a better metric for the perceived tactile dimensions used in our study than the lateral force magnitude.

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Appendix A
Electrostatic Force Simulation

A simulation model for the electrostatic force is designed using Python. The aim is to understand the influence of the input voltage used in our study on the generation of electrostatic force. The generated signal does not exhibit a pure sinusoidal waveform. It is a filtered noise signal that demonstrates distinct frequency characteristics. These characteristics are generated by the application of a filter, and the signal's amplitude modulation is achieved through the processes of normalisation and scaling. Refer to equations 1, 2, and 3 and Section III for a complete overview.

The electrostatic force equation model used in the simulation was taken from [43]:

$$\bar{F}_e = \frac{\epsilon_0 A U^2}{2\left(\frac{d^{sc}}{\epsilon^{sc}} + \frac{d^{\mathrm{a}}}{\epsilon^{\mathrm{a}}} + \frac{d^{\mathrm{i}}}{\epsilon^{\mathrm{i}}}\right)\left(d^{sc} + d^{\mathrm{a}} + d^{\mathrm{i}}\right)}. \tag{4}$$

where, Fe is the electrostatic force, ϵ_0 denotes the vacuum permittivity, A represents the fingertip contact area, and U signifies the modulated input voltage. d^{sc} and ϵ^{sc} denotes the thickness and relative permittivity of the stratum corneum, d^a and ϵ^a denotes the thickness and relative permittivity of the air gap, and d^i and ϵ^i denotes the thickness and relative permittivity of the insulator layer on touchscreen. The values of each of these parameters can be referred from Table VI taken from [43], [45].

TABLE VI
PARAMETERS VALUE FOR THE SIMULATION MODEL

Parameters	Value
A	100 mm^2
d^{sc}	25E-6 m
d^a	190E-3 μm
d^i	1E-6 m
ϵ_0	8.85E-12 F/m
ϵ^{sc}	3000
ϵ^a	1.0
ϵ^i	3.9

We present the simulation results in three cases for the different irregularity values. Additionally, the centre frequency was kept at 120 Hz with the amplitude of the signal as 120 V in all cases.

- Case 1: Irregularity: 0.0001

Here, the magnitude of the highest frequency component signal is 0.156 dB at 241Hz. A low value of irregularity implies a high-quality factor, resulting in the filter characteristic being highly selective in nature. This suggests that a very narrow band of frequency around the central frequency is allowed to pass through the filter. In this case, the perceived electrostatic force frequency component is close to double the value of the excitation frequency as observed in previous research studies [4]. Moreover, this results in a waveform that looks more like a pure sinusoidal wave (fig: 10), because it is mainly made up of one frequency.

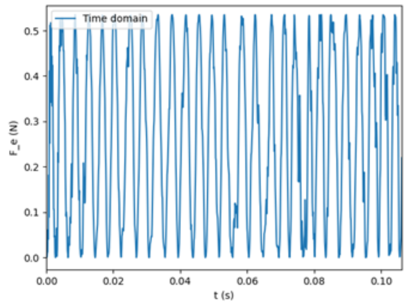


Fig. 10. Time domain of electrostatic force for the input voltage with 0.0001 irregularity

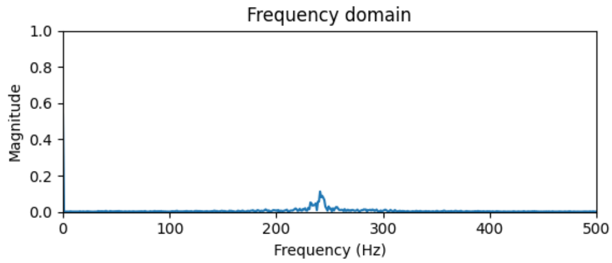


Fig. 11. Frequency domain of the generated electrostatic force over time for the input voltage with 0.0001 irregularity

- Case 2: Irregularity: 0.34

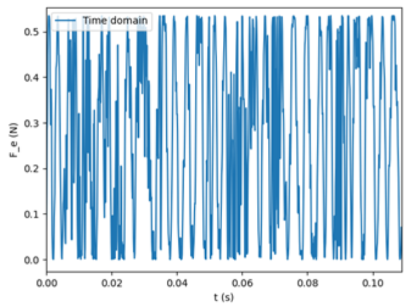


Fig. 12. Time domain of electrostatic force for the input voltage with 0.34 irregularity

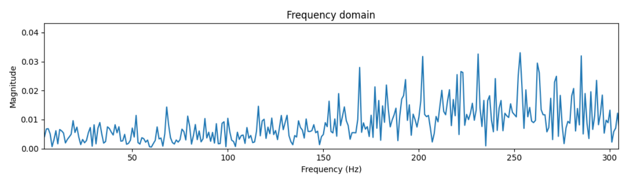


Fig. 13. Frequency domain of the generated electrostatic force over time for the input voltage with 0.34 irregularity

As the value of irregularity increases, the quality factor of the filter declines, resulting in a reduction in its selectivity nature. The waveform exhibits variations from its pure sinusoidal nature as it incorporates a broader range of frequencies in its composition. The presence of additional frequencies is interpreted as a form of distortion in the time-domain signal (fig 12 and 14). The term “distortion” in this context refers to the frequencies that are allowed to propagate past the filter.

- Case 3: Irregularity: 1.67

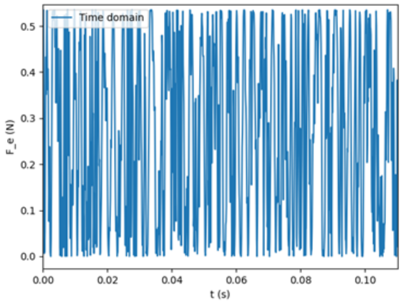


Fig. 14. Time domain of electrostatic force for the input voltage with 1.67 irregularity

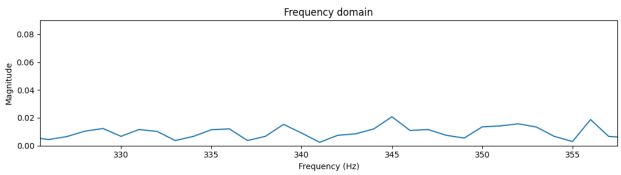


Fig. 15. Frequency domain of the generated electrostatic force over time for the input voltage with 1.67 irregularity

The magnitude of the highest frequency component signal is 0.0348 dB at 251 Hz and 0.0207 dB at 345 Hz for the 2nd and 3rd cases respectively.

The interpretation of the peak frequency component in the last two cases is extremely difficult. The values of the highest frequency components were printed on the Python console for reference. The specification of these frequency values does not guarantee that the electrostatic force in the frequency domain will consistently show its peak at these frequencies. The filter allows the distribution of signals within a particular frequency range. It is important to comprehend that white noise exhibits uniform energy distribution across all frequencies. However, this energy is currently being dispersed through a broader range of frequencies within the output signal. Therefore, there has been a substantial decrease in the magnitude of the peak signal component.

Appendix B
Additional Plots for User Tactile Perception

- Roughness Perception:

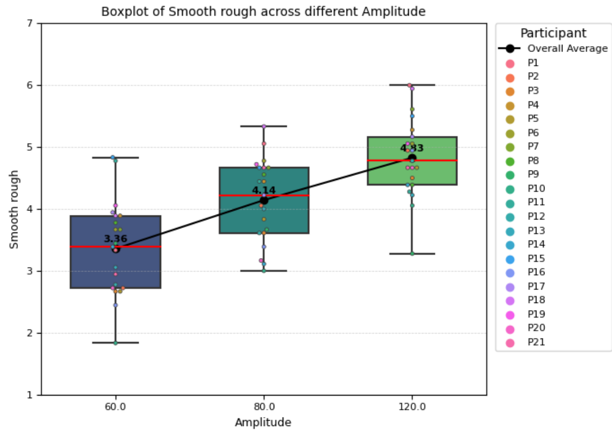


Fig. 16. Box-plot illustrating mean roughness perception versus amplitude for each participant. The overall average of the mean roughness rating across all participants for different amplitude values is represented by the black line

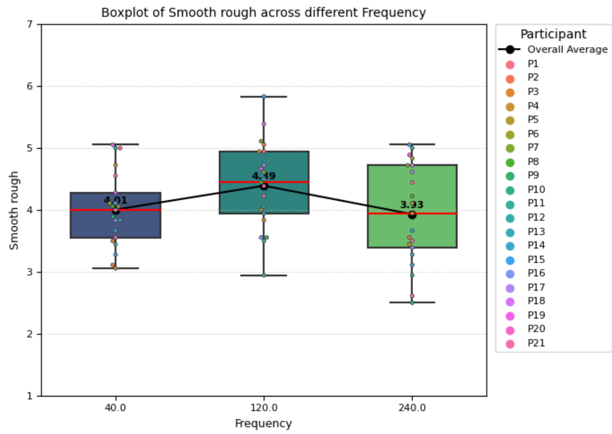


Fig. 17. Box-plot depicting mean roughness perception versus frequency for each participant. The overall average of the mean roughness rating across all participants for different frequency values is represented by the black line

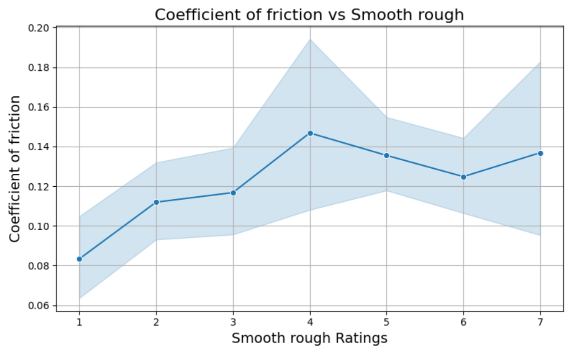


Fig. 18. Line plot showing coefficient of friction versus roughness perception rating paired with their respective confidence intervals

- Bumpiness perception:

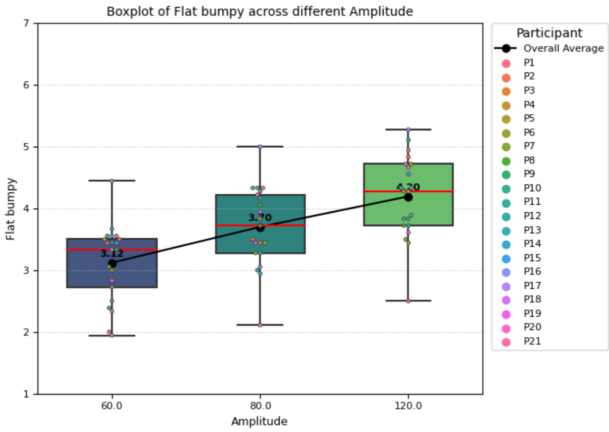


Fig. 19. Box-plot illustrating mean bumpiness perception versus amplitude for each participant. The overall average of the mean bumpiness rating across all participants for different amplitude values is represented by the black line

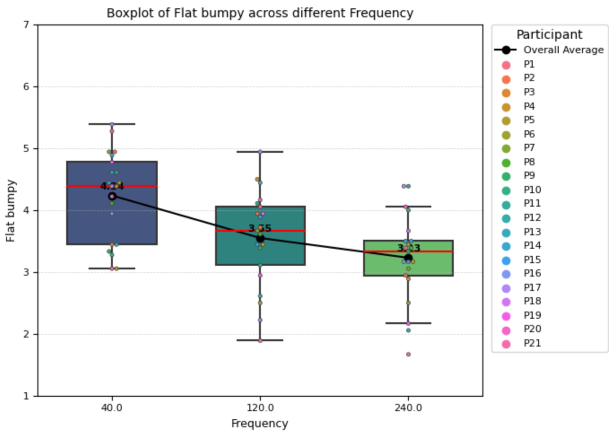


Fig. 20. Box-plot depicting mean bumpiness perception versus frequency for each participant. The overall average of the mean bumpiness rating across all participants for different frequency values is represented by the black line

- Slipperiness perception:

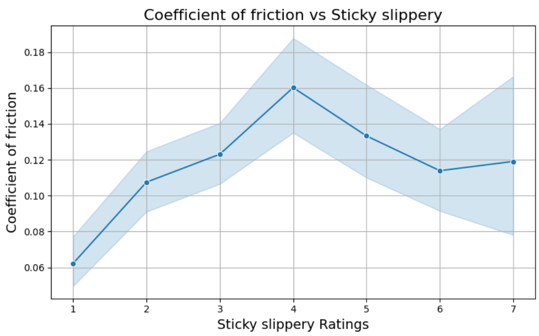


Fig. 21. Line plot depicting coefficient of friction versus slipperiness perception rating paired with their respective confidence intervals

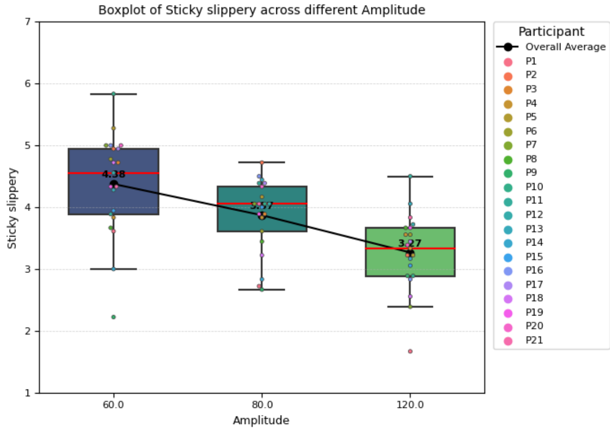


Fig. 22. Box-plot illustrating mean slipperiness perception versus amplitude for each participant. The overall average of the mean slipperiness rating across all participants for different amplitude values is represented by the black line

Appendix C
Supplementary Experiment Details

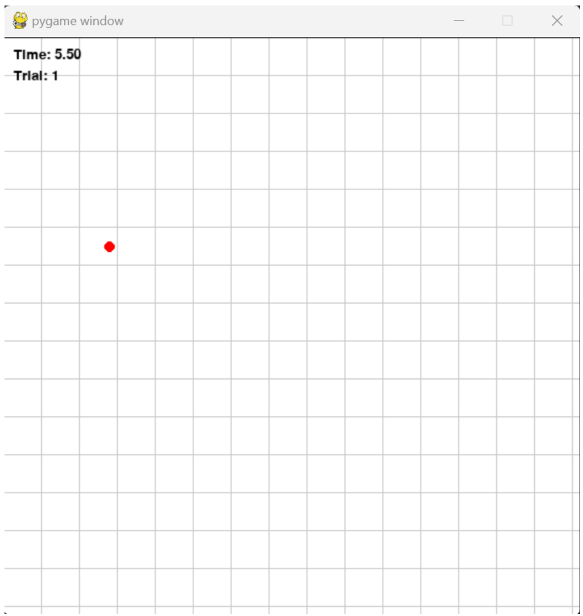


Fig. 23. Screenshot of the Pygame window (15 x 15 cm) GUI

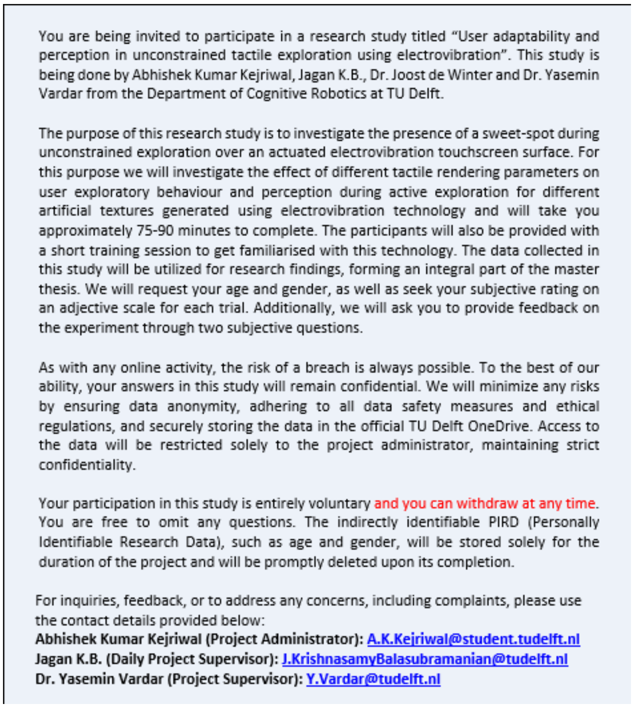
To identify the scaling factor of X and Y axis between the electrovibration touchscreen (15.8x13.4 cm, SCT3250, 3M Inc.) and Pygame window, we used the following approach:

- The resolution of our LCD monitor is 1920x1080, hence we used the default pixels per inch (PPI) value of 96. Then the pixels per centimeter (ppcm $\approx$ 37.8) is calculated using the formula:

$$\text{ppcm} = \frac{\text{PPI}}{2.54} \tag{5}$$

- The Pygame window size in pixels is calculated by multiplying its dimension (50x24 cm) with the calculated ppcm. Width: 50 cm x 37.8 ppcm = 1890 pixels, Height: 24 cm x 37.8 ppcm $\approx$ 907.2 pixels.

- Subsequently, we calculated the actual pixels per centimeter for the touchscreen. In X direction: 1890 pixels/15.8 cm $\approx$ 119.62 ppcm , in Y direction: 907.2 pixels/13.4 cm $\approx$ 67.70 ppcm .
- Finally, the scaling factors are established by taking the reciprocal of the actual pixels per centimeter. X scaling factor: 1/119.62 $\approx$ 0.00835981, Y scaling factor: 1/67.70 $\approx$ 0.01477105.
- The calculated scaling factors are approximations and may contain minor percentage of errors due to measurement inaccuracies and display variations.


You are being invited to participate in a research study titled “User adaptability and perception in unconstrained tactile exploration using electrovibration”. This study is being done by Abhishek Kumar Kejriwal, Jagan K.B., Dr. Joost de Winter and Dr. Yasemin Vardar from the Department of Cognitive Robotics at TU Delft.

The purpose of this research study is to investigate the presence of a sweet-spot during unconstrained exploration over an actuated electrovibration touchscreen surface. For this purpose we will investigate the effect of different tactile rendering parameters on user exploratory behaviour and perception during active exploration for different artificial textures generated using electrovibration technology and will take you approximately 75-90 minutes to complete. The participants will also be provided with a short training session to get familiarised with this technology. The data collected in this study will be utilized for research findings, forming an integral part of the master thesis. We will request your age and gender, as well as seek your subjective rating on an adjective scale for each trial. Additionally, we will ask you to provide feedback on the experiment through two subjective questions.

As with any online activity, the risk of a breach is always possible. To the best of our ability, your answers in this study will remain confidential. We will minimize any risks by ensuring data anonymity, adhering to all data safety measures and ethical regulations, and securely storing the data in the official TU Delft OneDrive. Access to the data will be restricted solely to the project administrator, maintaining strict confidentiality.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. The indirectly identifiable PIRD (Personally Identifiable Research Data), such as age and gender, will be stored solely for the duration of the project and will be promptly deleted upon its completion.

For inquiries, feedback, or to address any concerns, including complaints, please use the contact details provided below:
Abhishek Kumar Kejriwal (Project Administrator): A.K.Kejriwal@student.tudelft.nl
Jagan K.B. (Daily Project Supervisor): J.KrishnasamyBalasubramanian@tudelft.nl
Dr. Yasemin Vardar (Project Supervisor): Y.Vardar@tudelft.nl

Fig. 24. Screenshot of the provided text in the informed consent form

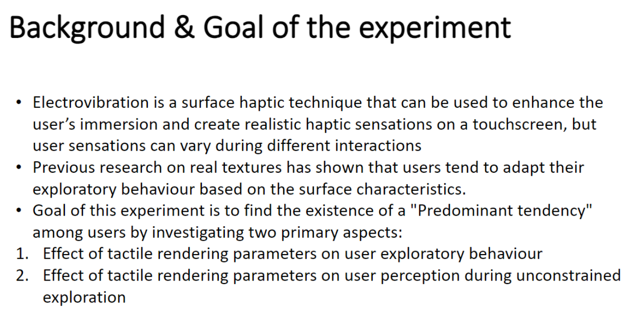


Fig. 25. Screenshot of the Participant presentation slide describing the background and goal of the experiment

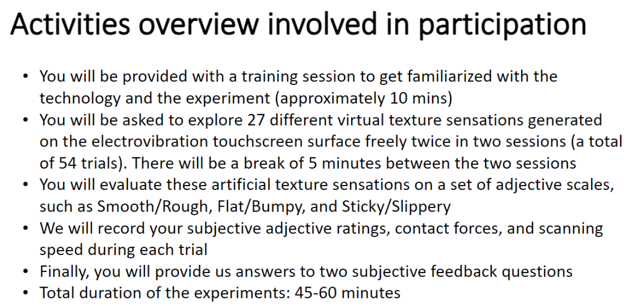


Fig. 26. Screenshot of the Participant presentation slide providing an overview of the activities involved in the experiment

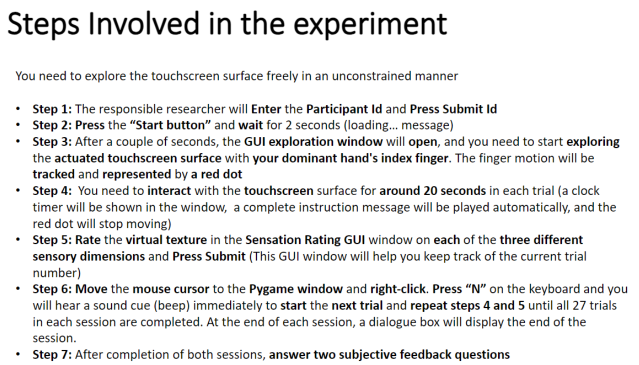


Fig. 27. Screenshot of the Participant presentation slide involving the steps or procedures of the experiment

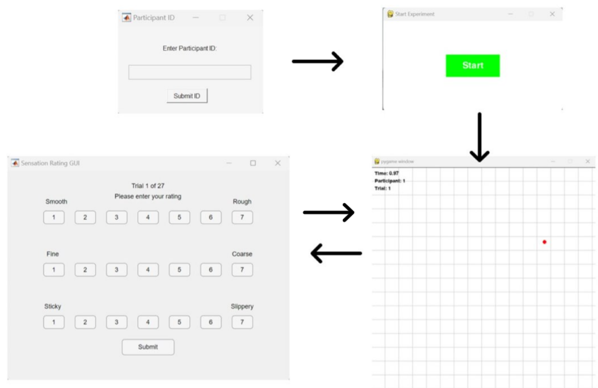


Fig. 28. Screenshot of the Participant presentation slide showing the timeline of different activities involved in the experiment using GUI

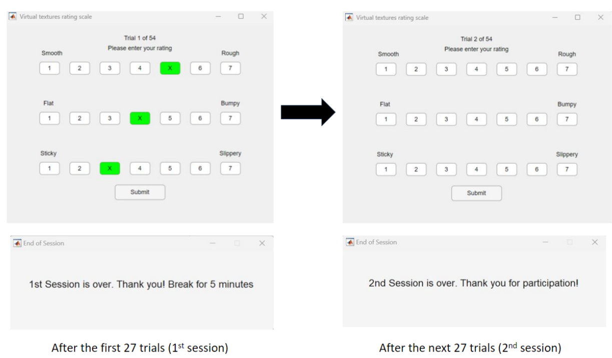


Fig. 29. Screenshot of the Participant presentation slide showing the rating and message displayed using GUI

The two subjective questions asked at the end of each experiment to each participant were: 1. How would you rate the overall quality of the virtual textures you felt during the experiment (1 to 5, with 1 being poor and 5 being best)? 2. Did you feel any discomfort or pain while experiencing the virtual textures during the experiment?

Additionally, the auditory message played at the end of each trial stated: “Trial completed, please enter your ratings and press N for the next trial”

Appendix D
Supplementary Plots

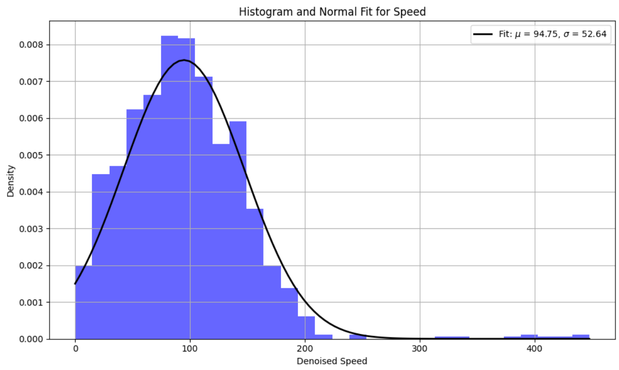


Fig. 30. Illustration of the mean speed calculation for one of the participant’s trial. Here the mean speed is 94.75 mm/s with a standard deviation of 52.64 mm/s

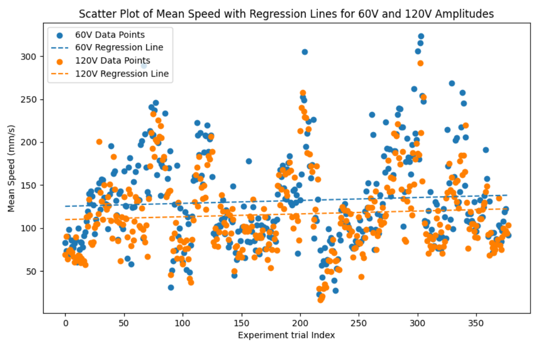


Fig. 31. Scatter plot for the mean speed across all trials and participants corresponding 60 and 120 V amplitudes with fitted regression lines

The disparity in the mean speed range between this analysis and that in fig. 5(a) and 5(b) is attributed to the aggregation of the mean speed data across all trials for each participant corresponding to each amplitude showcased in the box-plot. Alternatively, in the mean speed vs time graph, we plotted the mean speed across all trials and participants at each timestamp (378 data points, 21 x 18 corresponding to each amplitude value for that timestamp, we have 60 such timestamps between each second (60 FPS)). Here, we plotted the raw mean speed value corresponding to each amplitude for all participants directly.

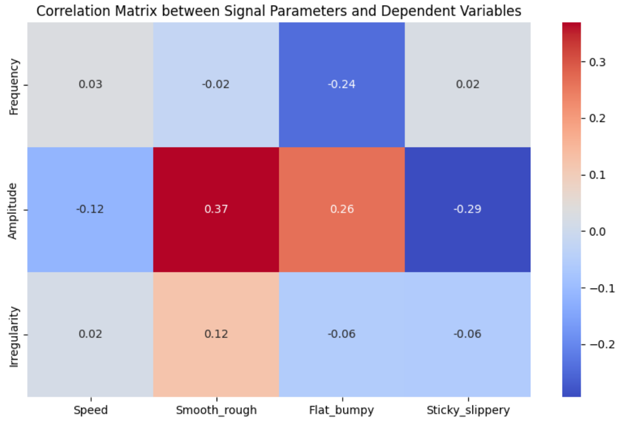


Fig. 32. Correlation matrix between the independent variables (signal parameters) and dependent variables (finger scanning speed and sensory adjective ratings) determined using Spearman correlation. The results align with our findings provided above showing amplitude as a key parameter influencing user scanning speed and perception. However, all correlation values are weak to moderate

Appendix E
Stimuli Set

TABLE VII
Stimuli Set from Session 1 (For 1 of the subject)

Frequency(Hz)	Amplitude(Vpeak)	Irregularity
120	120	0.0001
120	80	0.0001
240	80	0.0001
40	120	0.34
240	60	0.0001
40	120	1.67
240	120	0.34
40	60	0.0001
240	120	1.67
240	60	0.34
40	80	0.34
40	60	0.34
240	80	1.67
240	80	0.34
120	120	0.34
40	60	1.67
120	60	0.34
40	80	0.0001
40	80	1.67
120	60	1.67
120	80	0.34
240	60	1.67
40	120	0.0001
240	120	0.0001
120	120	1.67
120	60	0.0001
120	80	1.67

TABLE VIII
Stimuli Set from Session 2 (For the same subject)

Frequency(Hz)	Amplitude(Vpeak)	Irregularity
240	80	0.0001
240	60	1.67
120	120	1.67
240	120	0.0001
120	80	0.34
40	80	1.67
40	60	0.34
40	80	0.0001
240	60	0.34
40	120	0.34
120	120	0.0001
120	60	1.67
120	120	0.34
40	120	1.67
120	60	0.0001
40	60	1.67
120	80	1.67
240	120	0.34
120	60	0.34
40	80	0.34
40	120	0.0001
240	120	1.67
240	60	0.0001
240	80	0.34
240	80	1.67
120	80	0.0001
40	60	0.0001