Exploration of electrovibration for desktop computing

by

Arash JAMSHIDI

THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
IN PARTIAL FULFILLMENT OF A MASTER'S DEGREE
WITH THESIS IN ELECTRICAL ENGINEERING
M.A.Sc.

MONTREAL, NOVEMBER 7, 2023

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

BOARD OF EXAMINERS

THIS THESIS HAS BEEN EVALUATED

BY THE FOLLOWING BOARD OF EXAMINERS

M. Vincent Lévesque, Thesis supervisor
Département de génie logiciel et TI, École de technologie supérieure

Mr. Jean-Philippe Roberge, Chair, Board of Examiners
Département de génie des systèmes, École de technologie supérieure

Mr. Michael J. McGuffin, Member of the Jury
Département de génie logiciel et des TI, École de technologie supérieure

THIS THESIS WAS PRESENTED AND DEFENDED

IN THE PRESENCE OF A BOARD OF EXAMINERS AND THE PUBLIC

ON OCTOBER 18, 2023

AT ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

ACKNOWLEDGEMENTS

Throughout the past year and a half, I have had the pleasure of working with my supervisor Vincent Lévesque, and I would like to express my gratitude to him for his advice and encouragement throughout this period.

My sincere thanks go out to Siamak Rajabi and Shirin Kasaei for their support and assistance in helping me to develop and implement both the hardware and the software for both those components. In this regard, I would like to thank my colleagues in the labs for their help.

I am very grateful to my family members, especially to my sisters Arezou and Azadeh, for the years of support they have given me during my studies and life in general. There is no way that I would have been able to have such a fantastic experience of studying without their encouragement and love.

Exploration de l’électrovibration pour l’informatique de bureau

Arash JAMSHIDI

RÉSUMÉ

Récemment, le retour haptique a gagné en importance pour améliorer nos interactions. Des technologies telles que l’électrovibration ont permis l’incorporation de sensations tactiles, offrant de nouvelles façons d’enrichir les expériences utilisateur. En modulant la friction entre les surfaces et les extrémités des doigts, l’électrovibration peut simuler de manière convaincante des textures et des vibrations, remodelant notre façon d’interagir avec les environnements numériques. Les avancées dans les retours haptiques sur surfaces ont trouvé des applications dans divers domaines, même dans des situations quotidiennes. Par exemple, imaginez ressentir une réponse tactile en ajustant le volume ou en effectuant un achat en ligne sur l’écran tactile de votre smartphone, une expérience pour laquelle le retour visuel seule pourrait ne pas suffire.

Ce projet vise à étendre ces avancées en explorant l’intégration de dispositifs d’électrovibration dans des domaines spécifiques liés aux ordinateurs de bureau. Alors que le retour haptique a été utilisé avec des périphériques tel qu’une souris ou un clavier, l’électrovibration a rarement été utilisée dans ce contexte. L’électrovibration offre des avantages uniques qui se démarquent de mécanismes haptiques traditionels. Plus spécifiquement, l’électrovibration peut être appliquée à de larges surfaces de forme artitraire et produit des sensations plus naturelles lors d’une interaction.

Nous avons commencé par explorer en détail les options de conception pour les périphériques PC. Nos séances de remue-méninges ont révélé différentes façons d’utiliser l’électrovibration. Des esquisses haptiques nous ont aidés à affiner ces idées. En conséquence, nous avons choisi trois surfaces principales pour offrir aux utilisateurs une expérience tactile : le repose-poignet, le tapis de souris et les touches du clavier. Cela explique comment nous avons généré des idées, conduisant à plusieurs esquisses haptiques et propositions de conception.

En poursuivant à partir de là, nous nous sommes concentrés sur la création de prototypes fonctionnels pour évaluer les idées concernant les trois surfaces mentionnées. Ces prototypes combinent des composants matériels et logiciels. Nous avons créé un système de génération de signaux utilisé sur toutes les surfaces d’électrovibration à l’étude. De plus, nous avons conçu un prototype matériel unique pour chaque surface afin d’intégrer la technologie d’électrovibration. L’architecture logicielle correspondante a ensuite été conçue pour fonctionner avec le matériel, nous permettant de contrôler et d’activer les surfaces d’électrovibration selon les besoins.

Ensuite, nous présentons le plan d’expériences utilisateur sur chaque surface. L’objectif est de déterminer si les participants peuvent percevoir accidentellement le retour haptique électrovibrant, par exemple pendant des tâches telles que la frappe au clavier ou l’utilisation d’une souris, et intentionnellement en frottant leurs paumes et/ou leurs extrémités des doigts sur les surfaces d’électrovibration.

Grâce à cet effort, plusieurs réalisations importantes ont été obtenues. Tout d'abord, trois avenues distinctes et prometteuses pour l'intégration de l'électrovibration dans les périphériques PC ont été identifiées : le repose-poignet, le tapis de souris et les touches du clavier. En s'appuyant sur ces résultats, des prototypes fonctionnels ont été développés avec succès, mettant en œuvre la technologie d'électrovibration sur chacune de ces surfaces désignées. De plus, une expérience globale a été planifiée dans le but de valider l'efficacité de ces mises en œuvre et de contribuer à la compréhension des interactions tactiles dans ce domaine. En conséquence, ce travail a jeté les bases de l'amélioration des expériences utilisateur grâce à l'électrovibration dans les périphériques PC, en proposant trois prototypes concrets illustrant son potentiel. La prochaine étape consiste à réaliser l'expérience planifiée pour recueillir des informations précieuses et affiner l'utilisation de l'électrovibration dans ces contextes.

Mots-clés: haptique, électrovibration, application de bureau, périphériques PC

Exploration of electrovibration for desktop computing

Arash JAMSHIDI

ABSTRACT

In recent times, haptic feedback has gained significant importance in enhancing our interactions. Technologies like electrovibration have enabled the incorporation of tactile sensations, offering novel ways to enrich user experiences. By modulating friction between surfaces and fingertips, electrovibration can convincingly simulate textures and vibrations, reshaping how we engage with digital environments. This progress in surface haptics has found applications in various domains, even in everyday situations. For instance, imagine feeling a tactile response while adjusting the volume or making an online purchase with your smartphone's touchscreen, experiences that may not be adequately served by visual feedback alone.

This project aims to extend these advancements by exploring the integration of electrovibrating devices into specific areas related to desktop computers. While haptic feedback has been used with PC peripherals such as mice and keyboards, electrovibration has rarely been used in that context. Electrovibration offers unique advantages that set them apart from traditional haptic feedback mechanisms. More specifically, electrovibration can be applied to large surfaces of arbitrary shape and provides a more natural sensation when interacting with it.

We started by thoroughly exploring design options for PC peripherals. Our brainstorming revealed various ways in which electrovibration could be used. Haptic sketches helped us refine these ideas. As a result, we chose three main surfaces to give users a tactile experience: the palm rest, mouse pad, and keyboard keys.

Continuing from there, we then focused on crafting working prototypes to assess the ideas for the three surfaces mentioned. These prototypes combine hardware and software components. We created a signal generation system used across all the electrovibrating surfaces under investigation. Additionally, we devised a unique hardware prototype for each surface to integrate the electrovibration technology. The corresponding software architecture was then designed to work with the hardware, enabling us to control and activate the electrovibration surfaces as needed.

Next, we outline the plan for user experiments on each surface. The goal is to determine whether participants can perceive electrovibration feedback accidentally, such as during tasks like typing or using a mouse, and deliberately by rubbing their palms and/or fingertips on the electrovibrating surfaces.

Through this endeavor, several significant achievements have been realized. Firstly, three distinct and promising avenues for integrating electrovibration into PC peripherals were identified: the palm rest, mouse pad, and keyboard keys. Building upon these findings, functional prototypes were successfully developed, implementing electrovibration technology in each of these designated surfaces. Furthermore, a comprehensive experiment was planned, aiming to validate the effectiveness of these implementations and contribute to the field's understanding of tactile interactions. As a result, this work has contributed by laying the foundation for enhancing user experiences through electrovibration in PC peripherals, offering three tangible prototypes that exemplify its potential applications. The next step involves executing the planned experiment to gather valuable insights and refine the utilization of electrovibration in these contexts.

Keywords: haptic, electrovibration, desktop application, PC peripherals

TABLE OF CONTENTS

Page

INTRODUCTION 1

CHAPTER 1 LITERATURE REVIEW 5
1.1 Human haptics 5
  1.1.1 Physiology of the skin 6
  1.1.2 Tactile perception 8
    1.1.2.1 Detection of a vibrotactile stimulus 8
    1.1.2.2 Texture perception 8
  1.1.3 Exploratory procedure 10
1.2 Haptic technologies 11
  1.2.1 Grounded force-feedback 11
  1.2.2 Ungrounded haptic interface 12
  1.2.3 Surface haptics 12
1.3 Electrovibration 14
  1.3.1 Parameters affecting perception 15
  1.3.2 Perception on different areas of body 18
  1.3.3 Applications 19
1.4 Haptic feedback in PC peripherals 22
1.5 Conclusion 25

CHAPTER 2 DESIGN SPACE EXPLORATION 27
2.1 Ideation 27
2.2 Conceptual exploration 31
  2.2.1 Sketching of multi-touch mouse 32
  2.2.2 Sketching of mouse pad, palm rest and keyboard keys 35
  2.2.3 Medium-fidelity prototyping of mouse pad and palm rest 38
2.3 Conclusion 43

CHAPTER 3 PROTOTYPE DEVELOPMENT 45
3.1 Signal generating system 45
3.2 Electrovibrating surfaces 51
  3.2.1 Electrovibrating palm rest and electrovibrating mouse pad 52
  3.2.2 Electrovibrating keyboard keys 53
3.3 Software architecture 61
3.4 Conclusion 63

CHAPTER 4 EXPERIMENTAL DESIGN 65
4.1 Methodology 66
4.2 Experiment 1: electrovibrating palm rest 68
  4.2.1 Test 1a: accidental detection 69

4.2.2 Test 1b: deliberate detection 72
4.3 Experiment 2: electrovibrating mouse pad 74
4.3.1 Test 2a: accidental detection 74
4.3.2 Test 2b: deliberate detection 81
4.4 Experiment 3: electrovibrating keyboard keys 81
4.4.1 Test 3a: accidental detection 81
4.4.2 Test 3b: deliberate detection 84
4.5 Limitations 85

CONCLUSION AND RECOMMENDATIONS 87

APPENDIX I RESULT OF IDEATION SESSIONS 89

BIBLIOGRAPHY 95

LIST OF TABLES

Page

Table 1.1 Sensory basis of kinesthetic perception Taken from Jones (2018) 6

Table 2.1 Results of first brainstorm 29

Table 2.2 Results of the second brainstorm 30

Table 4.1 Sentences used in test 1a, each consisting of 7 words 69

LIST OF FIGURES

Page

Figure 1.1 Human skin structure and the flow of tactile information 7

Figure 1.2 Three archetypical haptic interface designs 12

Figure 1.3 The parts of the force that a finger experiences when haptically interacting with a touch surface 13

Figure 1.4 Classification of current surface haptics display technologies based on stimulation direction and method 13

Figure 1.5 Electrovibration operating principle 16

Figure 1.6 a) Example of an anchored gesture: choosing an item from a menu with one finger that stays in place while the other rotates to select it b) Drawing is done with the dominant hand as an example of handling asynchronous tasks with two hands and Orientation is controlled by the non-dominant hand. 20

Figure 1.7 TouchPhoto use case 21

Figure 1.8 Application of electrovibration in online shopping scenario 22

Figure 1.9 Investigating the use of haptic feedback in augmented reality experiences with physical objects 23

Figure 1.10 Enhancing tangible items with haptic response for use in augmented reality experiences that use video imagery 24

Figure 2.1 Magic mouse 33

Figure 2.2 Sketches and 3D model of mouse with electrovibrating multi-touch surface. (a) Perspective view, (b) Side view, (c) Top view, (d) Actual perspective view, (e) Actual top view 34

Figure 2.3 Mockup of 3D model depicting mouse surface and structure 35

Figure 2.4 Keyboard haptic sketch 36

Figure 2.5 Haptic sketches: a) palm rest with sandpaper 120-grit, b) palm rest with fabric cotton, c) mouse pad with sandpaper 120-grit, and d) mouse pad fabric cotton 37

Figure 2.6 Graphical user interface for temporal rendering: second variation 40

Figure 2.7 Graphical user interface for spatial rendering: preliminary exploration 44

Figure 3.1 An overview of the prototypes hardware components, highlighting the electrovibrating surfaces represented by the green areas 46

Figure 3.2 Electrovibrating surfaces prototypes: highlighted in green 46

Figure 3.3 Raspberry Pi with AD/DA board 47

Figure 3.4 The extended circuit employed in the prototype to generate a bipolar output using DAC8552 48

Figure 3.5 5V 8-Channel Relay interface board 49

Figure 3.6 An overview of the prototypes’ hardware components 50

Figure 3.7 Anti-static wrist strap 51

Figure 3.8 3M capacitive touchpanel 52

Figure 3.9 Electrovibrating palm rest 53

Figure 3.10 Electrovibrating mouse pad 54

Figure 3.11 Electrovibrating keyboard keys 54

Figure 3.12 3D-printed keyboard keys 55

Figure 3.13 Keyboard keys 3D designs: (a) and (b) depict the bottom and top of the key respectively, (c) and (d) the bottom and top of the key respectively, and so on 56

Figure 3.14 Creating keyboard key using copper foil tape (the central deformation line results from the wire positioned beneath the tape) 58

Figure 3.15 Creating keyboard key using aluminum plate 59

Figure 3.16 EL609 green insulating varnish 60

Figure 3.17 Hardware setup: electrovibrating palm rest, mouse pad, keyboard keys, and signal generator 62

Figure 4.1 PC interface for accidental detection test 1a 70

Figure 4.2 Pop-up question in accidental detection test 1a 71

Figure 4.3 PC interface in deliberate detection test 1b 73

Figure 4.4 Demonstration of source-target circles in test 2a 75

Figure 4.5 Pop-up question in test 2a 75

Figure 4.6 (a) and (b) depict regular computer mouse, (c) and (d) show mini mouse, and (e) and (f) display ergonomic vertical mouse 78

Figure 4.7 Directions illustration in test 2a 80

Figure 4.8 An illustration of a trial in accidental detection test 3a 83

Figure 4.9 An example depicting a trial in the deliberate detection 3b test 85

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

cm	Centimeter
Hz	Hertz
mm	Millimeter
V	Volt
Ω	Ohms
kHz	KiloHertz
A	Ampere

INTRODUCTION

In recent years, there has been a growing interest in the field of haptic feedback, which aims to enhance the user experience by providing tactile sensations through the sense of touch. Surface haptics, such as electrovibration, has emerged as a promising approach to delivering realistic tactile feedback. On touchscreens and other surfaces, by modulating the friction between a user's fingertips and a touch surface, electrovibration can create the illusion of textures, vibrations, and other haptic sensations.

The progress made in surface haptics has expanded the scope of their utilization across diverse domains, encompassing everyday scenarios in the real world. Consider the scenario where you engage with the touchscreen of your smartphone, and despite the absence of physical elements, you perceive the tactile feedback of adjusting the volume or perceiving the tactile feedback of touching the texture of an online purchase. This technology has the capability to transform user interfaces significantly, offering a heightened level of immersion and interactivity.

This project aims to explore the possibility of enhancing the user experience by integrating electrovibrating devices within specific areas related to desktop computers. In the initial phase, various design possibilities of electrovibration in PC peripherals were explored, leading to the selection of three surfaces. These surfaces include integrating electrovibration feedback on the palm rest, on the mouse pad, and on the keyboard keys. The aim is to provide texture sensations on the user's skin when in contact with these areas. Additionally, several prototypes were developed to test these concepts. The research progressed further by designing experiments to validate and assess the effectiveness of these concepts.

The foundation for this research builds upon the previous work conducted by Friaa *et al.* (2022), who developed an electrovibrating keyboard by placing two 3M capacitive plates beneath a keyboard. Their study focused on measuring the detection thresholds of electrovibration at the palm and fingertip. The study's results indicate that the hand region does not significantly impact tactile perception of electrovibration, leading to the conclusion that the palm is highly sensitive to electrovibration and supporting the concept of an electrovibrating keyboard producing strong and rich tactile sensations on the palm. In continuation of their work, our study aims to investigate whether users of computer desktops can perceive tactile feedback when interacting intentionally or unintentionally with the area beneath the keyboard, a concept derived from their work, as well as two additional areas that we have further explored: beneath the mouse and on the keys of the keyboard.

The primary goals of this research are to examine the potential design space of electrovibration in PC peripherals and to study how electrovibration feedback is perceived in various scenarios. By integrating electrovibrating devices with computer peripherals, we aim to understand users' ability to perceive tactile feedback and identify the types of interactions where this technology can be effectively used within software applications.

The outcomes of this project are expected to provide valuable insights into users' perception when electrovibration devices are integrated with parts of the computer desktop. These insights can aid designers in creating more sophisticated electrovibrating devices and leveraging this technology in software development. By incorporating electrovibration feedback, it becomes possible to provide subtle and ambient notifications for various events, such as indicating low battery levels, reminding users of scheduled meetings, or alerting them to the current state of the PC. These innovative ideas were derived from the exploration of the design space in Chapter 2.

The structure of this thesis is organized as follows: Chapter 1 presents a comprehensive overview of haptic feedback and electrovibration technology, incorporating relevant literature on the perception of electrovibrating devices. The literature review explores human haptics, including tactile perception and its physiological aspects, as well as various haptic technologies such as grounded force-feedback, ungrounded haptic interfaces, and surface haptics. Additionally, the chapter delves into electrovibration, examining parameters affecting perception, applications, and the perception of different areas of the body. The final section concentrates on haptic feedback in PC peripherals, serving as a foundation for further research on the integration of electrovibration into computer desktop devices. Chapter 2 describes the brainstorming sessions and the generation of ideas and haptic sketches to explore the potential areas for prototyping electrovibration feedback. In chapter 3, the hardware and software design of electrovibrating prototypes for the three investigated areas is presented. These areas include the electrovibrating mouse pad, the electrovibrating palm rest, and the electrovibrating keyboard keys. Chapter 4 outlines the design of user experiments that will be conducted as future work in each of the designed areas.

CHAPTER 1

LITERATURE REVIEW

The literature review in this chapter provides a comprehensive examination of various aspects of human haptics, haptic technologies, the specific technology of electrovibration, and haptics for PC peripherals. The chapter is divided into four sections. Section 1.1 delves into human haptics, covering topics such as the physiology of tactile perception, the detection of vibrotactile stimuli, and texture perception. Section 1.2 discusses haptic technologies, including grounded force-feedback devices, ungrounded haptic interfaces, and surface haptics. In Section 1.3, we explore the concept of electrovibration, investigating the parameters affecting perception, its applications, and the differences in perception across various body areas. Lastly, Section 1.4 focuses on haptic feedback in PC peripherals, examining its integration and impact on user experience.

1.1 Human haptics

Haptic refers to the sense of touch or the perception of tactile sensations. It is a sensory system that allows humans to interact with the physical world by feeling and sensing different textures, pressure, temperature, and vibrations through the skin and other body parts. Haptic technology aims to simulate tactile experiences and deliver rich, interactive feedback to enhance user interactions with digital devices and systems.

Touch, unlike the other four senses (sight, hearing, taste, and smell), travels throughout the body via our skin, joints, muscles, and tendons. Touch is usually divided into two types: kinesthetic and tactile. Kinesthetic sensations are felt in the muscles, tendons, and joints as forces and torques. Tactile sensations such as pressure, shear, and vibration are detected by mechanoreceptors, which are sensory end organs embedded in the skin (Culbertson *et al.*, 2018).

Kinesthesia, or kinesthetic perception, refers to the sensory experience of perceiving movement and force. It is frequently associated with the relationship between force and displacement (Culbertson *et al.*, 2018). When tactile perception remains unaffected by cutaneous stimulation, this particular perception can be identified as kinesthetic (Loomis *et al.*, 1986). An overview of the perceptual components of kinesthesia is provided in Table 1.1.

Table 1.1 Sensory basis of kinesthetic perception
Taken from Jones (2018)

Sensory event	**Source of information**
Perception of limb movement	Muscle spindle receptors Cutaneous mechanoreceptors Joint receptors
Perception of limb position	Muscle spindle receptors Cutaneous mechanoreceptors Joint receptors
Perception of force	Golgi tendon organs Corollary discharges

Tactile perception, also known as cutaneous perception, refers to the human capacity to detect and interpret objects through the skin. The skin's outer surface, encompassing both hairy and non-hairy regions of the body, is covered by cutaneous receptors responsible for this sensory experience (Lederman *et al.*, 2009).

A conventional view has been that the cutaneous senses consist of four submodalities that convey tactile, thermal, painful, and pruritic (itch) information to the central nervous system. However, new evidence suggests that touch has a fifth modality that conveys positive affective properties (pleasantness) (McGlone *et al.*, 2010).

1.1.1 Physiology of the skin

The skin has several layers of receptors. The epidermis refers to the visible surface, which is actually a layer of tough dead skin cells. The dermis is the layer beneath the epidermis. Mechanoreceptors, receptors that respond to mechanical stimulation such as pressure, stretching, and vibration, are found in these two layers (Goldstein, 2013). Many of the tactile perceptions that we feel from stimulation of the skin can be traced to the four types of mechanoreceptors that are located in the epidermis and the dermis. We can distinguish between these receptors by their distinctive structures and by how fibers associated with the receptors respond to stimulation. They consist of (1) Pacinian corpuscles, (2) Meissner's corpuscles, (3) Merkel's disks, and (4) Ruffini endings, collectively known as low-threshold mechanoreceptors (Goldstein, 2013; McGlone *et al.*, 2010) (Figure 1.1). The first two are classified as fast adapting (FA) as they respond to the initial and final contact of a mechanical stimulus on the skin, and the last two are classified as slowly adapting (SA), continuing to fire during a constant mechanical stimulus. A further classification relates to the low-threshold mechanoreceptors' receptive field, i.e., the surface area of skin to which they are sensitive, which is determined by the low-threshold mechanoreceptors' anatomical location within the skin. Those near the surface, at the dermal/epidermal boundary (Meissner's corpuscles and Merkel's disks) possess small receptive fields, and those lying deeper within the dermis (Pacinian corpuscles and Ruffini endings), have large receptive fields (McGlone *et al.*, 2010).

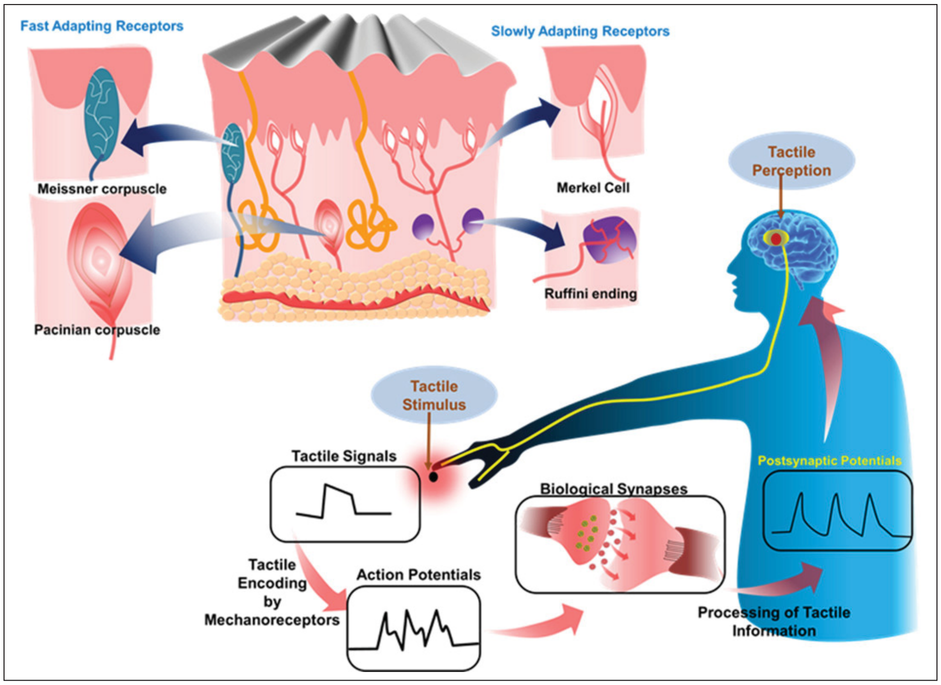


Figure 1.1 Human skin structure and the flow of tactile information
Taken from Ozioko *et al.* (2022)

1.1.2 Tactile perception

Sensory receptors in our skin allow us to perceive a wide range of stimuli, including not only mechanical vibrations (vibrotactile) but also other types of mechanical sensations such as skin stretch and poking. Additionally, our skin receptors enable us to sense thermal stimuli and detect painful sensations. This section will provide an overview of the perception of mechanical stimuli, including vibrotactile sensations, skin stretch, poking, and other related sensations in glabrous skin.

1.1.2.1 Detection of a vibrotactile stimulus

The detection of vibrotactile stimuli involves the interaction between the human finger and a surface. The natural response of the surface combines with the synthetic tactile stimulus (Basdogan *et al.*, 2020). The current understanding of how humans perceive tactile sensations is based on the four-channel theory, which explains that the skin has four types of mechanoreceptors that detect skin deformation and transmit electrical signals to the brain. Each type of receptor corresponds to a psychophysical channel that is sensitive to different input frequencies, which partially overlap. The Pacinian channel is most sensitive to frequencies between 40-500 Hz, with its highest sensitivity at around 250 Hz. The NPII channel has a similar sensitivity range to the Pacinian channel, but it is more sensitive if the stimulated area is large. The Meissner receptor mediates the NPI channel, which is most sensitive to frequencies between 2-40 Hz. Finally, the NPIII channel is mediated by Merkel receptors, with a sensitivity range of 2-16 Hz (Vardar, 2020).

1.1.2.2 Texture perception

Texture perception refers to an individual's ability to detect and distinguish the physical characteristics of an object's surface, such as its smoothness, roughness, softness, and hardness. This process involves the brain's interpretation of tactile information received from the skin's receptors. Previous research by Holliins *et al.* (1993) and Hollins *et al.* (2000) has identified two primary perceptual dimensions in texture perception: roughness-smoothness and hardness-softness. These dimensions have been found to be distinct and independent from each other. However, a different study conducted by Okamoto *et al.* (2012) proposed the existence of additional dimensions, such as stickiness/slipperiness and temperature, and also suggested a friction dimension related to the perception of moistness/dryness and stickiness/slipperiness. Since electrovibration, the technology used in this thesis, cannot modify the softness or temperature of a surface, the following summary will focus on roughness and friction perception only:

- **Roughness:** Roughness refers to the perceived coarseness or irregularity of a surface. It is the sensation that results from the interaction of a surface with the skin, causing variations in the pressure and vibrations experienced by the sensory receptors in the skin. In general, roughness is perceived when a surface has an uneven or irregular pattern of features, such as bumps, ridges, or grooves. These irregularities create variations in the tactile experience, leading to the perception of roughness.

  In a series of studies exploring the perception of roughness during direct touch, researchers have identified various factors that influence how individuals gauge the roughness of different surfaces. Lederman (1981) and Lederman *et al.* (1972) focused on the role of force exerted by the finger pad on the object and its impact on roughness perception during both active and passive touch. Interestingly, they discovered that the magnitude of perceived roughness and the consistency of judgments were similar for both types of touch, suggesting that force plays a crucial role in roughness estimation.

  Similarly, Taylor *et al.* (1975) investigated the significance of surface characteristics, particularly groove width, in determining roughness perception, which directly correlated with the applied finger force. Their findings further supported the idea that force plays a pivotal role in how individuals perceive roughness.

  In a different approach, Smith *et al.* (2002) delved into the influence of tangential force variation during touch on the perceived roughness of various surfaces. They found that the rate of fluctuation in the sideways force (tangential force) was a significant factor in determining the perceived roughness. Additionally, the average friction between the finger and the surface (kinetic friction) was related to roughness, but the fluctuations in tangential force were even more crucial. Moreover, Smith *et al.* (2002) observed that when a surface was lubricated, both the average friction and the fluctuations in tangential force decreased, leading people to perceive the surface as less rough.

The studies discussed indicate that the important factors that affect how rough a surface feels are related to the characteristics of the object itself, such as the shape of its surface, which varies across space, and also the way it interacts with applied forces and sliding speed, which can vary over time.

- **Friction:** Friction perception is influenced by both tangential and normal forces, which require some degree of sliding motion between the surface and the finger to be detected. As indicated by Basdogan *et al.* (2020), alterations in the friction coefficient — the ratio of the tangential force to the normal force applied — result in a decrease of the coefficient of friction until a constant value is reached, despite an increase in the normal force that enhances the tangential force. It is crucial to acknowledge that the friction experienced between a smooth surface and a fingerpad is affected by various factors related to the finger, including moisture, velocity, mechanical characteristics, fingerprints, age, and gender. When it comes to smooth surface interactions, the amount of moisture buildup in the gap between the finger and surface can cause the fingerpad to soften through a process known as plasticization. This softening, in turn, can lead to an increase in the coefficient of friction (Basdogan *et al.*, 2020).

1.1.3 Exploratory procedure

In the context of haptic feedback, an exploratory procedure refers to the process by which a person uses their sense of touch to explore and gather information about an object or environment. This can be done through various haptic feedback technologies which provide users with touch-based sensory information (Goldstein, 2013).

During an exploratory procedure, a person typically uses their fingers and hands to feel and manipulate an object, using various techniques such as sliding, tapping, and squeezing. By doing so, they can gain a better understanding of the object's texture, shape, size, and other physical properties. In general, exploratory procedures are divided into two submodalities.

- **Active:** Active touch involves a user intentionally moving their hand across a surface or manipulating an object to gather specific information, thereby controlling the relative movement between themselves and the object (Hatzfeld *et al.*, 2016).
- **Passive:** Passive touch refers to the interaction with an object where the relative movement is caused by external factors, such as the experimental setup, rather than by the user's intentional movement (Hatzfeld *et al.*, 2016).

1.2 Haptic technologies

Haptic interfaces are devices made of hardware and software that allow for computer-controlled and programmable mechanical sensations related to touch (Hayward *et al.*, 2004), or in other words, they allow for person-to-machine communication through touch. Haptic interfaces have the unusual ability to enable simultaneous information exchange frequently in response to user movements (Hayward *et al.*, 2007). The three following archetypal haptic interface designs that have shown the most promise for producing touch-based interaction are grounded force-feedback, ungrounded haptic interface, and surface haptics. As seen in Figure 1.2, a person can interact with a distant or virtual environment using any one of these three haptic interface types (Kuchenbecker, 2018).

1.2.1 Grounded force-feedback

The concept of grounded force-feedback involves the use of a robotic device that is securely attached to a stationary surface. This device enables users to hold or connect to the end-effector of the interface, allowing for precise monitoring and control of position, orientation, force, and/or torque at that specific location. These interfaces usually consist of rigid links connected by rotating and/or sliding joints. Alternatively, some designs incorporate tensioned cables within a frame (Kuchenbecker, 2018).

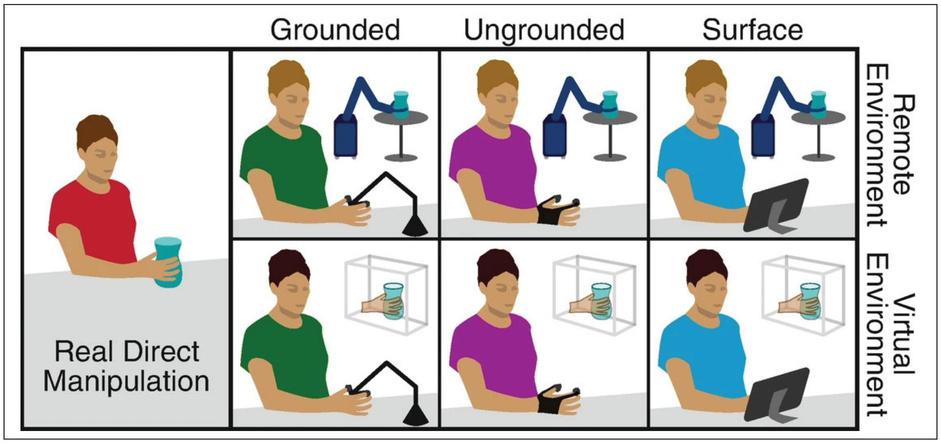


Figure 1.2 three archetypical haptic interface designs
Taken from Kuchenbecker (2018)

1.2.2 Ungrounded haptic interface

The term "ungrounded haptic interface" refers to haptic devices that are not connected or fixed to a stable surface but instead held in the hand or directly attached to the human body. These devices are sometimes known as body-grounded haptic interfaces or wearable devices. In such systems, the motion sensing is often achieved through the use of inertial, optical, or magnetic sensors, which allow for non-contact detection of motion. However, the absence of grounding poses certain challenges in generating haptic sensations that can be easily perceived and distinguished by the user. Additionally, the design of ungrounded haptic interfaces must address considerations such as weight, comfort, and adaptability to users of different sizes (Kuchenbecker, 2018).

1.2.3 Surface haptics

The goal of surface haptics is to give users tactile feedback by adjusting the forces that the fingers experience when interacting with touch surfaces. Based on the direction in which they stimulate the finger, these interaction forces can be divided into two types of actuation technologies, as shown in Figure 1.3: those that stimulate the finger tangential to the surface (F_t and F_o) and those that stimulate it normal to the surface (F_n). In a study, Basdogan *et al.* (2020) outline a methodology for categorizing existing technologies according to the general force decomposition approach. Figure 1.4 illustrates this classification in more details.

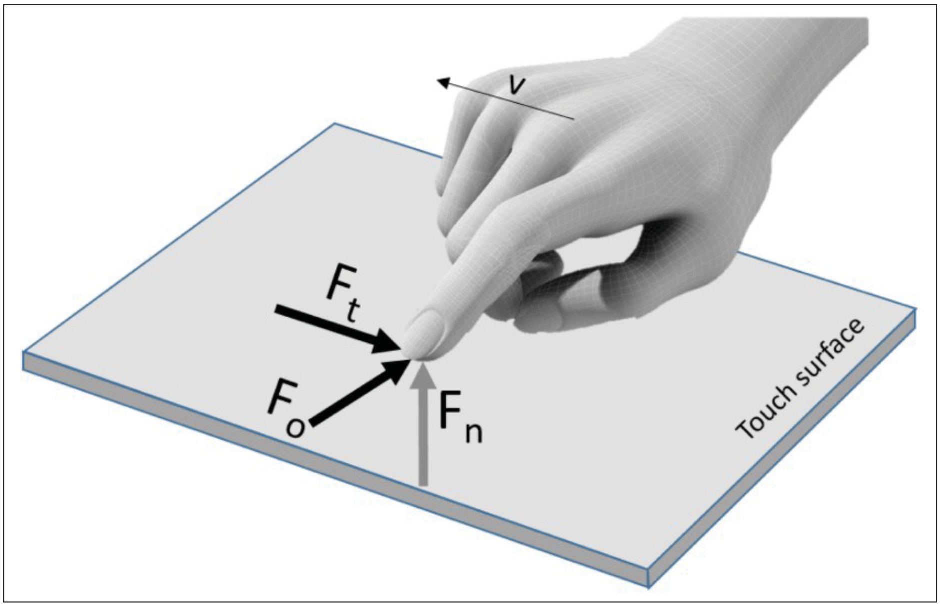


Figure 1.3 The parts of the force that a finger experiences
when haptically interacting with a touch surface
Taken from Basdogan *et al.* (2020)

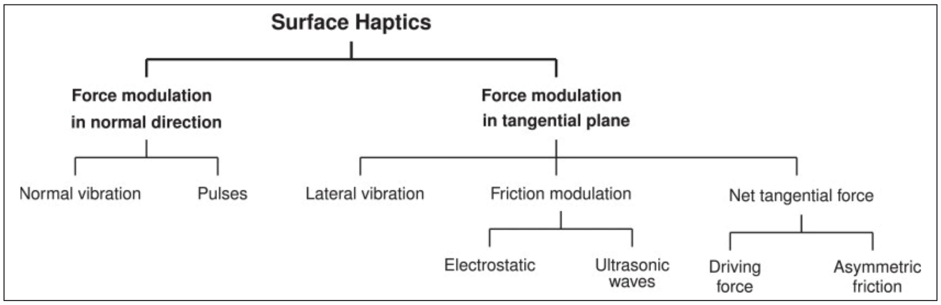


Figure 1.4 Classification of current surface haptics display
technologies based on stimulation direction and method
Taken from Basdogan *et al.* (2020)

Researchers have developed techniques to dynamically modify friction between a tactile surface and a sliding finger. One method involves the use of actuators to produce ultrasonic waves on the surface, which reduces the friction coefficient and creates intermittent contact with the finger, known as active lubrication. This approach enables the generation of simple tactile effects via on-off actuation or more complex effects through closed-loop amplitude control.

Alternatively, electrovibration can be used to increase friction by applying a voltage to the conductive layer of a capacitive touchscreen or an electrovibrating surface, creating electrostatic attractive forces in the normal direction between the surface and the finger. This results in a perceivable frictional force in the tangential direction opposite to the finger's movement. By adjusting the voltage signal's amplitude, frequency, and waveform, different tactile effects can be produced through modulation of this frictional force. Although the force generated in the normal direction is small compared to the finger's normal load, it is sufficient to alter the frictional force applied to the finger (Basdogan *et al.*, 2020).

In surface haptics, the most prevalent designs involve modifying the tangential friction force that the user's finger experiences as it glides over a surface. This can be achieved either by actively altering the coefficient of friction or by applying an extra attractive force in the perpendicular direction. However, ensuring a consistent tactile sensation across a large area, creating transparent actuators, and integrating them with tactile sensors present challenges. Additionally, reducing power consumption for mobile devices is also a significant concern. The user's finger must also be in motion to detect changes in friction force (Kuchenbecker, 2018).

1.3 Electrovibration

Given the emphasis of this thesis on electrovibration, as a subset of surface haptics, we will extensively explore the concept of electrovibration in this section.

The phenomenon of electrovibration was discovered accidentally by Mallinckrodt *et al.* (1953). They observed that dragging a dry finger over a conductive surface covered with a thin insulating layer and excited with a 110 V AC signal resulted in a unique "rubbery" sensation. The researchers suggested that the insulating layer of dry outer skin formed the dielectric layer of a capacitor, with conductive surfaces and fluids in the finger's tissue serving as the two opposing plates. When an alternating voltage was applied to the conductive surface, an intermittent attraction force developed between the finger and surface, which modulated friction between the surface and skin of the moving hand, resulting in a rubbery sensation. This phenomenon was named “electrovibration”.

Electrovibration creates a tactile sensation by directly stimulating the skin. The TeslaTouch system (Bau *et al.*, 2010) serves as a notable example of electrovibration technology and was one of the pioneering works that popularized this approach, especially in the context of touchscreens.

The TeslaTouch system uses a 3M Microtouch panel, which was originally designed for capacitive touch sensing. This panel consists of a transparent electrode sheet applied to a glass plate coated with an insulator layer. By applying a periodic electrical signal to the connectors that are typically used for position sensing, we can employ electrovibration to create an electrically induced attractive force between the user’s finger and the electrode. This force increases the dynamic friction between the finger and the panel surface, resulting in tactile feedback (Figure 1.5). The resulting deformations are perceived as vibration or friction and can be controlled by modulating the amplitude and frequency of the applied signal.

In our current work, comprehending the principles of electrovibration and studying advancements like TeslaTouch offers valuable insights into the potential and challenges of integrating tactile feedback solutions. Additionally, exploring other studies and applications utilizing electrovibration enhances our understanding of how this technology can enhance interactions in diverse contexts.

1.3.1 Parameters affecting perception

Tactile perception of friction can be influenced by various parameters. In this section, we will discuss the major parameters.

- **Amplitude and Frequency:** The study conducted by Wijekoon *et al.* (2012) aimed to assess the intensity of friction modulation produced by electrovibration on a flat surface that mimicked a touch screen interface. The researchers introduced a fixed 6-point Effect Strength Subjective Index (ESSI) to measure the general sensation intensity and compared it

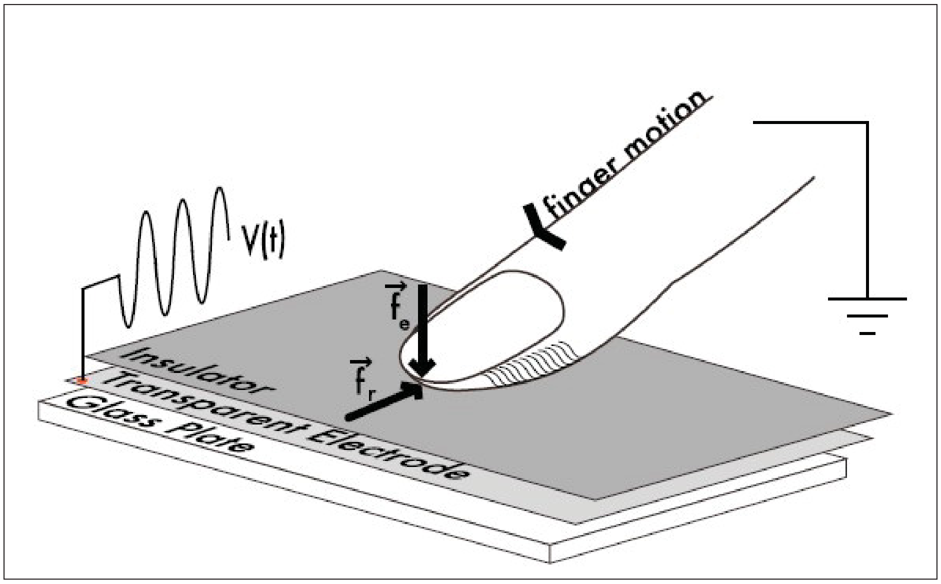


Figure 1.5 Electrovibration operating principle
Taken from Bau *et al.* (2010)

with an open magnitude scale. The findings revealed a significant link between intensity perception and the amplitude of the applied voltage signal, with frequency of 80 Hz showing the highest sensitivity.

Building on this research, Bau *et al.* (2010) also explored the relationship between the effect of amplitude and stimulus frequency. They showed that an increase in amplitude increases perceived smoothness of tactile sensations for high frequency textures (e.g., 400 Hz). At the 80 V_{pp} amplitude, the textures were compared and notable distinctions were observed when the amplitude was increased to 115 V_{pp}. The "cement surface" and "cheap paper" textures were perceived as smoother in contrast to the "paper" or "painted walls" textures. For example, one participant compared stimuli at 80 V_{pp} to a "painted wall" and later described 115 V_{pp} textures as "smoother painted walls".

Additionally, Bau *et al.* (2010) discovered that low-frequency stimuli were perceived as rougher than high-frequency stimuli. They were frequently compared to "wood" and "bumpy leather" as opposed to "paper" and "a painted wall" for stimuli with a higher frequency.

- **Waveform:** The focus of (Vardar *et al.*, 2020) is on exploring the impact of input voltage waveform on our tactile perception of electrovibration on touch screens. To do this, a series of psychophysical experiments were conducted with the participation of eight subjects. The aim of the experiments was to measure the detection thresholds of electrovibration stimuli generated by both sinusoidal and square voltages at seven fundamental frequencies (15, 30, 60, 120, 240, 480, 1920 Hz). The findings revealed that the volunteers were more responsive to square wave stimuli compared to sinusoidal ones for fundamental frequencies below 60 Hz.

- **Polarity:** In (Kaczmarek *et al.*, 2006), an experiment was designed to determine the polarity sensitivity of the electrovibratory transduction mechanism. In this study, four waveforms were tested, all of which produced equivalent electrostatic forces. However, they found that thresholds were higher for positive pulses compared to negative or biphasic pulses, suggesting polarity-sensitive force production. This observation suggests that negative or biphasic pulses may be more effective in eliciting tactile sensations compared to positive pulses.
- **Skin properties:** Tang *et al.* (1998) investigated how the structure and surface condition of the finger skin contribute to the interindividual variability of the electrostatic stimulation mechanism. The findings revealed that the same stimulating voltage may produce different tactile sensations among individuals due to their unique skin characteristics. Moreover, skin characteristics were found to play a significant role in determining the effectiveness of the electrostatic stimulation mechanism. In the experiments, one subject did not detect any usable sensation on the display, which could be attributed to various factors, such as an excessively thick and unconductive outer layer of skin, a low-friction coefficient of the skin surface on the display, and a moist skin surface that resulted in a sweat layer shielding the electric field. The skin on a person's finger has dynamic characteristics, such as secretions, that can affect the accuracy of estimating the electrostatic force and degrade the sensation. When the finger makes contact with a display surface for a longer time, the secretions can accumulate and create a conductive layer of sweat between the skin and display surface. This sweat layer shields the electric field that would normally form between the electrodes and skin, causing a significant decrease in the electrostatic force on the skin. Additionally, the sweat layer's physical characteristics may prevent the production of a shear force.

- **Environmental effects:** The level of atmospheric humidity is another factor that can impact the electrostatic stimulation experienced on a display (Tang *et al.*, 1998). During winter months, when heating systems are in use, the humidity is often low, resulting in a stronger tactile sensation. However, in the spring, if the humidity is not properly controlled, the tactile sensation can worsen. This is because the plastic insulator can absorb moisture, leading to increased conductivity of its surface, which, in turn, degrades the electric field's effect on the skin of the finger.

1.3.2 Perception on different areas of body

While limited studies specifically address electrovibration on different body parts, research on vibration perception can offer valuable insights.

In a study conducted by Oey *et al.* (2004), the perception of vibrations in two different parts of the human hand, the fingertips and the palm, was examined. Vibration thresholds and equal vibration levels were measured from 16 to 315 Hz, covering the range of three mechanoreceptors in the hand, the Merkel and Meissner receptors, and the Pacini corpuscles. The study found that for frequencies up to 80 Hz, the vibration thresholds were lower in the fingertips than in the palm. However, above 80 Hz, the vibration thresholds were similar at both locations. Similarly, the equal vibration levels were higher in the fingertips than in the palm for frequencies up to 80 Hz, but were similar at both locations above 80 Hz. These findings indicate that the fingertips are more sensitive to vibrations at low frequencies, likely due to the higher density of mechanoreceptors in that area.

In a recent study, Friaa *et al.* (2022) investigated how people perceive electrovibration on their fingertips and palms. The study involved 14 volunteers, and the results showed no significant difference in the ability to detect electrovibration between these two areas. Interestingly, the researchers found that the palm is very sensitive to electrovibration, even though it has fewer mechanoreceptors than the fingertips. However, there was a higher variability in detection thresholds for the palm, which could be due to individual differences in sensitivity or variations in hand position.

1.3.3 Applications

Electrovibration is a versatile technology that has the potential to improve the user experience in various applications, including but not limited to gaming, virtual reality, and mobile devices. The technology has a wide range of possible applications, some of which are outlined below.

Bau *et al.* (2010) implemented many applications that are designed for electrovibration on touchscreens such as providing conventional GUI widgets with tactile feedback. One potential use case is to incorporate it into sliders to provide feedback on the drag extent. By changing the frequency of the tactile feedback, users can receive information about how far they have dragged the slider. Another example of how electrovibration could be used is by incorporating it into a list of emails. By running their fingers over the list, users can receive tactile feedback that indicates which emails are new or important.

Electrovibration provides tactile feedback only when fingers are in motion, allowing for multitouch feedback as long as only one finger is moving on the surface. This feature is used by TeslaTouch (Bau *et al.*, 2010) in two distinct and beneficial ways:

- **Anchored Gestures:** These gestures involve manipulating an object with one finger while using another finger as a reference point. For instance, to select an item from a pie menu, one finger stays stationary while the other rotates. Similar to this, shape transformations like stretching, rotation, or zooming can be carried out by designating a static reference point with one finger and determining the degree of transformation with the other. During these operations, electrovibration can give the moving finger haptic feedback.
- **Two-Handed Asynchronous Manipulation:** In this method, the task is asymmetrically split up between the two hands. For instance, a virtual sheet of paper might be oriented with the non-dominant hand while the dominant hand is engaged in fine-grained interaction like writing on touchscreen. A third option would be to control a standard slider using modal

buttons (Figure 1.6). With electrovibration, tactile feedback can be added to these gestures, enhancing the overall user experience.

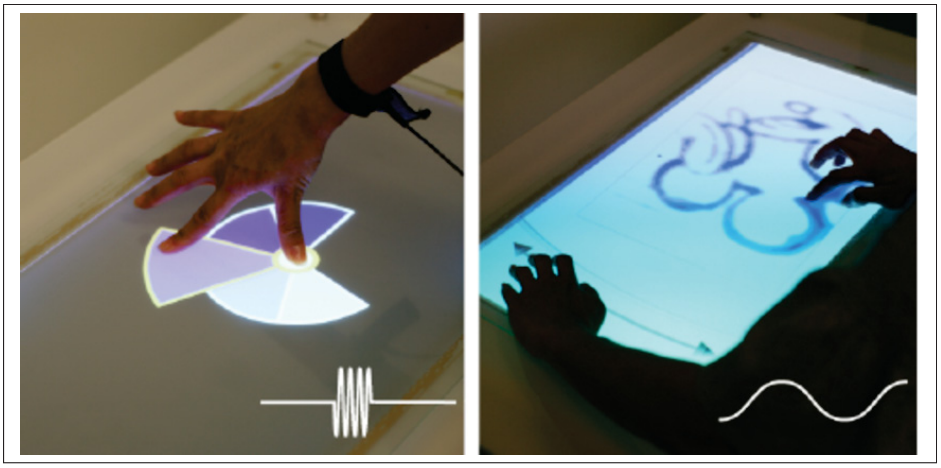


Figure 1.6 a) Example of an anchored gesture: choosing an item from a menu with one finger that stays in place while the other rotates to select it. b) Drawing is done with the dominant hand as an example of handling asynchronous tasks with two hands and orientation is controlled by the non-dominant hand Taken from Bau *et al.* (2010)

Several pioneering works have also leveraged electrovibration to create innovative systems aimed at enhancing user experiences. Lim *et al.* (2019) introduced TouchPhoto, a comprehensive system that aims to empower visually-impaired individuals in capturing, organizing, and comprehending photographs autonomously. The system provides auditory guidance to help users take pictures and record audio tags to aid in recalling the photograph's contents. Additionally, users can listen to the embedded audio tags and explore the photograph's details through an electrovibrating display. The system also includes a tactile rendering algorithm that allows users to perceive the height and texture of human faces using gradient-based lateral force modulation (Figure 1.7).

Lu *et al.* (2019) also explored the potential of electrovibration in the context of virtual environments by showcasing a novel tactile device that uses electrovibration to simulate surface texture of virtual objects, and is equipped with a flexible film controlled by a DC motor to generate

Figure 1.7 TouchPhoto use case
Taken from Lim *et al.* (2019)

desired softness based on the applied finger force. The device was successfully integrated with a virtual environment, and an online shopping scenario was demonstrated (Figure 1.8).

Building upon the concept of electrovibration, Bau *et al.* (2012) discussed the REVEL technology, which is an augmented reality (AR) tactile technology that allows for the modification of the tactile sensation of real objects by incorporating virtual tactile textures. REVEL technology enables the provision of tactile feedback to interactive surfaces without the need for traditional vibrotactile actuation, which is difficult to implement on large surfaces. The technology is scalable and can be used on various types of interactive surfaces, including solid structures such as walls and floors. In an example implementation, conductive paint and floor tiles were used, and the tactile signal was injected into the user's foot via a REVEL device embedded in their shoe. The technology can be applied to various materials, including transparent ITO film and anodized aluminum plates (Figure 1.9).

The REVEL technology also allows users to change the texture and feel of physical objects by augmenting them with virtual tactile textures in real-time. The technology involves nickel-plating the surface of the object and injecting a tactile signal into the user through the device's case. The device is equipped with a capacitive touchscreen that allows users to feel the tactile properties of augmented physical objects directly on the touchscreen. The technology can be applied to various AR tactile applications and reinforces the perception of physicality in virtual elements,

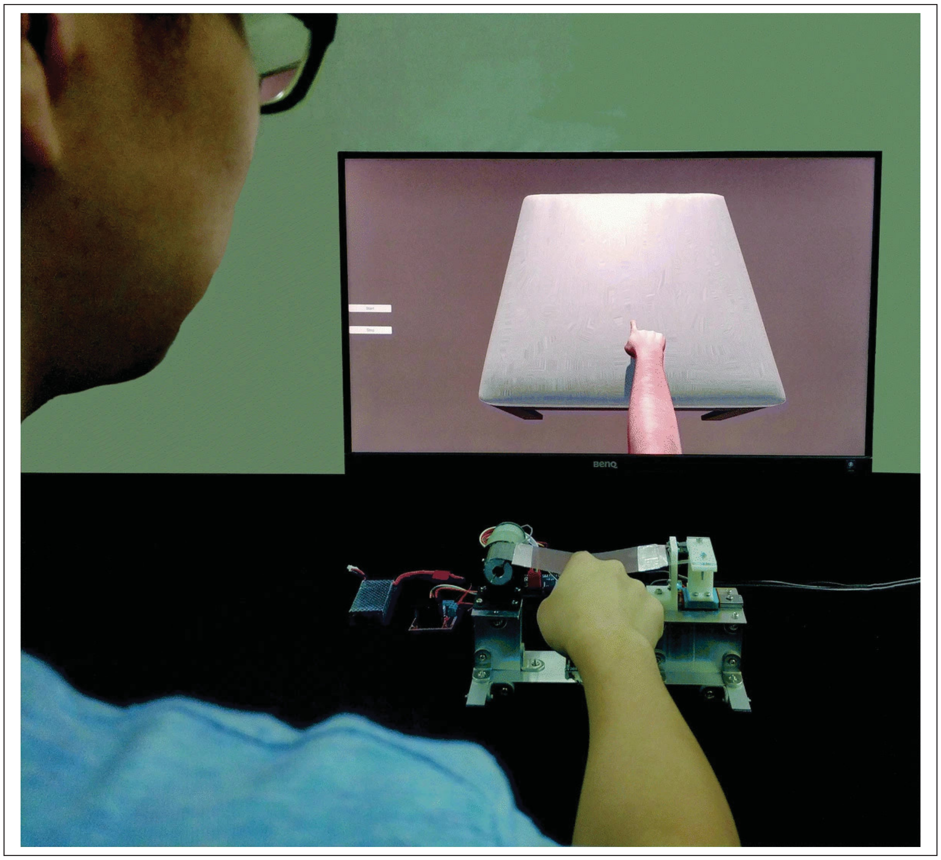


Figure 1.8 Application of electrovibration in online shopping scenario
Taken from Lu *et al.* (2019)

reducing the gap between virtual and physical sensations in augmented reality (Bau *et al.*, 2012) (Figure 1.10).

Together, these works showcase the exciting potential of electrovibration-based haptic feedback in a variety of applications, ranging from empowering visually-impaired individuals to providing realistic tactile experiences in virtual environments.

1.4 Haptic feedback in PC peripherals

Our research builds upon previous work by Friaa *et al.* (2022) and explores the application of electrovibration in interactive objects, particularly in a keyboard that provides tactile feedback on the palm as it touches the surface below (discussed in section 1.3.2). Additionally, Bau *et al.*

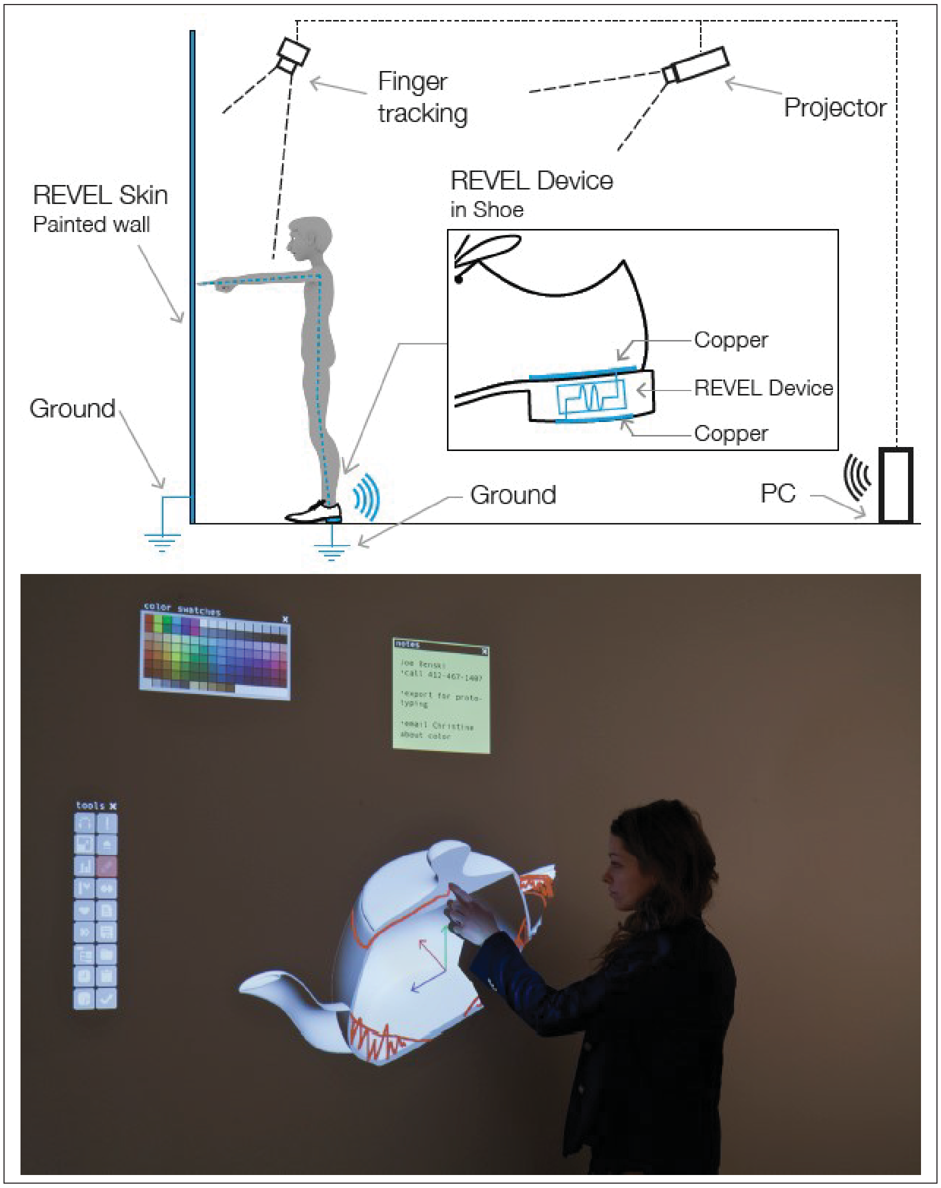


Figure 1.9 Investigating the use of haptic feedback in augmented reality experiences with physical objects
Taken from Bau *et al.* (2012)

(2012) introduced the novel technology called REVEL (discussed in section 1.3.3), expanding tactile interfaces beyond touch surfaces into the real world. REVEL uses reverse electrovibration to create distinct tactile textures on physical objects, without requiring physical actuation or tactile gloves. It offers potential applications for enhancing augmented reality interactions in both real and virtual environments.

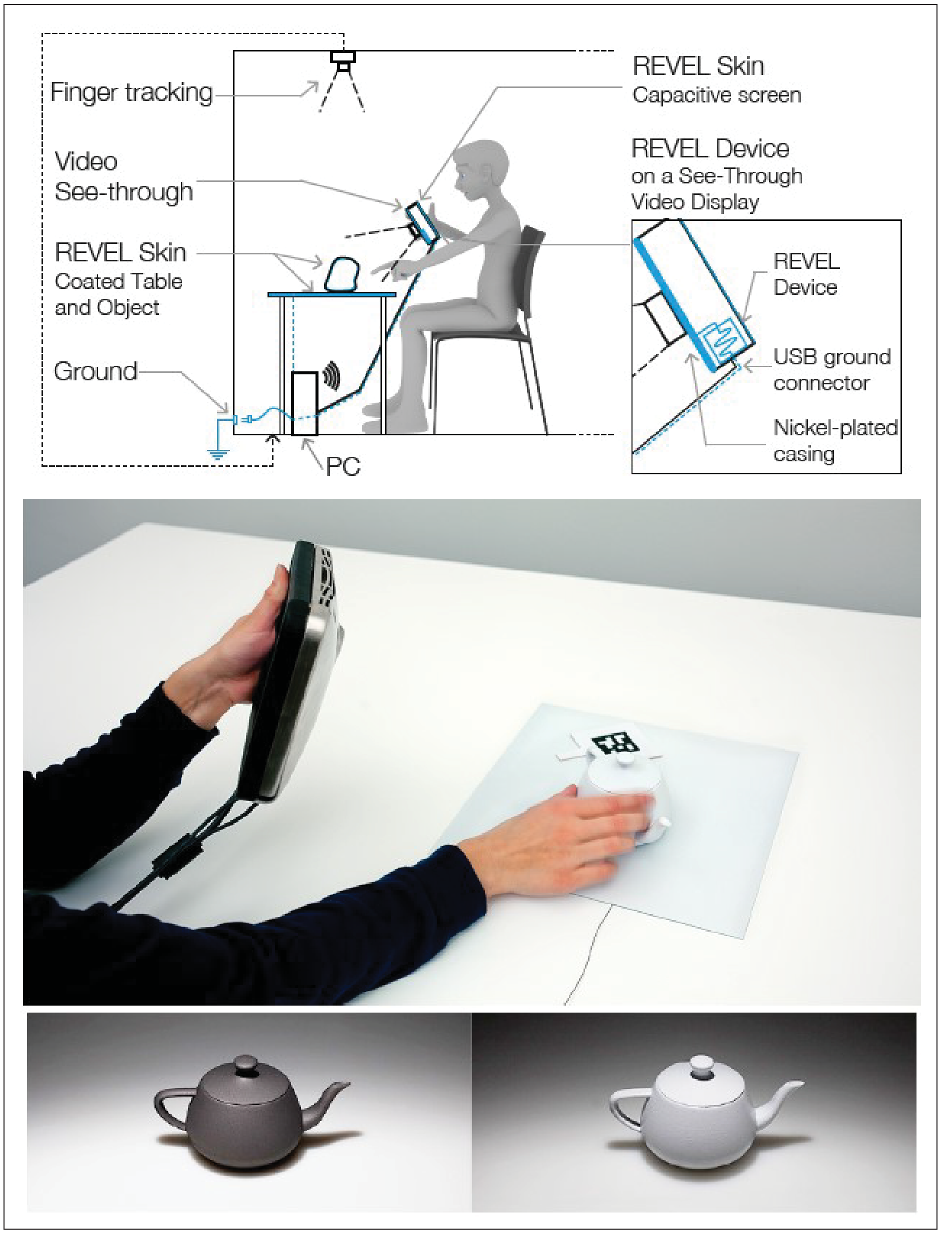


Figure 1.10 Enhancing tangible items with haptic response for use in augmented reality experiences that use video imagery
Taken from Bau *et al.* (2012)

Other studies investigate the addition of haptic features to computer mice, with one focusing on a near-surface haptic pointing interface that enables users to feel basic geometrical shapes in a GUI (Karunanayaka *et al.*, 2013). Another study presents a tactile computer mouse with actuators to provide users with tactile feedback while preserving the mouse's interaction capabilities (Strese *et al.*, 2018). The SPIDAR-mouse (Asai *et al.*, 2015), a string-based haptic device, advances haptic feedback in PC peripherals by enabling realistic tactile sensations corresponding to side-to-side forces.

Furthermore, there are studies involving haptic mouse systems that combine force feedback capabilities with conventional mice to enhance the human-computer interface. These systems enable users to feel the virtual environment, providing tactile feedback beyond the visual channel and enhancing e-commerce interactions (Choi *et al.*, 2003). Modifications to mice, such as solenoid-driven pins and electromagnets, introduce tactile and force display capabilities, reducing target selection times and exploring the impact of different sensory modalities (Akamatsu, 1994).

Some research also focuses on haptic computer keyboards, where precise control over the force and position of each key is crucial. Self-sensing principles and linear electrodynamic actuators are for example employed by Savioz *et al.* (2009) to achieve position control in a compact haptic keyboard. Additionally, Savioz *et al.* (2011) present the design and optimization of a small-sized linear electrodynamic actuator for force feedback, contributing to the development of a reliable and compact haptic keyboard.

1.5 Conclusion

This chapter encompasses a comprehensive overview of studies exploring the potential of electrovibration technology for generating tactile sensations on touch screens, various surfaces, and physical objects. Additionally, it examines how different parts of the body perceive vibrations, yielding valuable insights. Furthermore, the integration of haptic feedback in PC peripherals, including mice and keyboards, showcases innovative designs aimed at enhancing user interactions and delivering more immersive experiences. Collectively, the research underscores the promising applications of electrovibration-based haptic feedback.

It’s important to note that our work addresses a previously unexplored area within this field. Specifically, we delve into the potential of electrovibration in the context of PC peripherals and surfaces. Our work builds upon the foundation established by previous research, particularly the work of Friaa *et al.* (2022), who designed a keyboard palm rest using two capacitive plates. However, our study takes a progressive step by not only augmenting the prototype design for keyboard palm rest but also by identifying and developing additional tactile surfaces for a range of PC peripherals.

CHAPTER 2

DESIGN SPACE EXPLORATION

This chapter reports an introductory exploration focusing on the design thinking approach to investigate the potential of electrovibration in PC peripherals. We aimed to use this exploration to decide what should be prototyped. To begin, we initiated multiple brainstorming sessions to delve into the design space of electrovibration, allowing us to consider its diverse applications in PC peripherals. Furthermore, we used haptic sketches as a tool to examine and refine the identified potential use cases for PC peripherals. These activities enabled us to inspect the feasibility and effectiveness of electrovibration in PC peripherals through preliminary tests conducted on various surfaces, such as an electrovibrating mouse surface, an electrovibrating mouse pad, an electrovibrating palm rest, and electrovibrating keyboard keys. These initial explorations played a crucial role in informing the subsequent chapter, where prototypes were implemented based on the promising outcomes.

2.1 Ideation

The exploration of the design space of electrovibration for PC peripherals began with two brainstorming sessions.

All the brainstorming sessions were conducted online to facilitate documentation and recording ideas. This online approach was particularly helpful as some lab members were unable to be physically present, allowing them to contribute their ideas remotely. We used the collaborative platform Miro to streamline the process. The participants involved in the sessions were myself, my research advisor, and other lab members. Prior to the sessions, we prepared a Miro workspace that contained guiding questions to steer our brainstorming process. Each participant contributed their ideas by pinning them onto the virtual board using different colored stickers.

During the initial one-hour session, our main focus was on the central question: Which areas of the computer desktop can we explore for the application of electrovibration? Together, we categorized potential areas into four groups: input devices, other peripherals, office supplies, and environment. This classification emerged from our brainstorming discussions. Within each group, we further refined and discussed specific areas that exhibited potential for utilizing electrovibration technology. Engaging in discussions, we expanded upon each idea and explored practical implementation possibilities. The outcomes of this session are documented in Table 2.1.

In the second brainstorming session, our goal was to build upon the applications identified in Table 2.1, specifically focusing on PC peripherals and their potential uses within the previously identified groups. The guiding question for this session was: How could we use electrovibration in real-world applications for various peripherals? The most interesting of the results are presented as an extension of Table 2.1 in Table 2.2, which provides further details on these applications.

Table 2.1 Results of first brainstorm

Category	**Feedback Location**	**Application**
Input devices	Input ports	USB port confirmation
	Mouse pad	Mouse movement on mouse pad
	Game controller	Immersive gaming feedback
	Keyboard keys	Enhanced typing experience
	Touchpad	Improved cursor control and accuracy for scrolling and clicking
	Resting area of the keyboard	Customizable haptic feedback for hand resting and movement
	Scroll wheel	Variable scrolling sensations during scrolling actions
	Touchscreen	Enhanced sensations during interactions (tapping, swiping, scrolling)
Other peripherals	Speaker	Enhancing bass response
	Headphones	Elevating the overall audio experience during audio playback
	Webcam	Enabling precise adjustments of zoom or focus in high-end webcam
	Monitor stand	Enabling precise adjustments of the height or angle of the monitor
	Scanner, Microphone, Monitor frame, printer	Other purposes
Office supplies	Paper	Simulate flipping physical pages on digital devices
	Stapler	Provide tactile confirmation of proper stapling
	Pen holder	Provide tactile confirmation of a securely placed pen
	Pen or pencil	Enhances control and feedback, improve stroke precision
Environment	Under the desk	Confirm intended contact with the area
	Side of the desk	Confirm intended contact with the area
	Chair legs with wheels	Smooth motion confirmation enhances user's sense of movement
	Chair seat/backrest	Confirm ergonomic seating with back support
	Floor	Confirm smooth movement with added sense of motion or impact
	Phone (landline), Cup, Armrest, Wall, Lamp	Other purposes

Table 2.2 Results of the second brainstorm

PC Peripheral	Application
Keyboard	Giving feedback when sliding on keys as input to enhance typing experience
	Highlighting keys on the keyboard to locate letters, numbers, or symbols easier
	Indicating battery status on the power button to eliminate the need for a separate battery level indicator
	Assist in learning to type by identifying mistakes and incorrect key presses
	Notify users about permissions for accessing restricted apps or files
	Indicate nearby typing to foster communication in shared spaces
Mouse	Notify users about permissions for accessing restricted apps or files
Mousepad	Notify users about permissions for accessing restricted apps or files
	Meeting notifications to remind users of upcoming appointments
Touchscreen	Meeting notifications to remind users of upcoming appointments
	Render textures to enhance immersion in gaming
	Provide tactile feedback on devices to alert users about incoming messages or notifications
	Simulate the feeling of different fabrics on a touch screen when shopping for clothes online
	Indicate nearby typing to foster communication in shared spaces
	Enhance security with unique tactile patterns for login authentication
Touchpad	Enhance security with unique tactile patterns for login authentication
	Improve time awareness through feedback on the passing of time

Based on the results of brainstorming sessions, we now want to identify which computer peripheral surfaces are more promising to incorporate electrovibration. Our aim is to use electrovibration feedback, relying on the generation of frictional forces. Therefore, it is necessary to focus on peripherals that are in direct contact with human skin and are used most frequently. The results of the first brainstorming session propose four categories of PC peripherals, which are listed in Table 2.1. Among these categories, input devices stand out as they come in direct contact with human skin, such as the hand, palm, forearm, and fingers. Moreover, input devices involve more motion and friction due to their interaction with the PC.

The results of the second brainstorming session primarily revolve around GUI-based applications, as indicated in Table 2.2. These applications are closely tied to the input devices category and specifically focus on the keyboard, touchscreen, mouse, and mouse pad surfaces. Based on these brainstormed ideas, these areas appear to hold the greatest potential to benefit from electrovibration feedback.

In summary, our analysis indicates that incorporating electrovibration into input devices like keyboards, touchscreens, mice, and mouse pads shows the most promising potential for integrating this feedback modality into desktop computer. Since the application of electrovibration in touchscreens, such as TeslaTouch (Bau *et al.*, 2010), has been extensively studied, we choose to focus on the integration of electrovibration in keyboards (including keyboard keys and palm rest), mice, and mouse pads.

2.2 Conceptual exploration

Building upon the results of our previous brainstorming sessions, where we identified various computer input devices that have the potential for electrovibration, we are now taking a more detailed approach by exploring and sketching these areas to determine their potential. Our objective is to assess whether these areas are indeed promising for our purposes, and if so, we can proceed with planning the design of our prototypes accordingly.

First, we report the sketching of a multi-touch mouse, where we explore the possibility of using electrovibration technology on the surface of a mouse. Next, we provide the design and sketches for an electrovibrating mouse pad, electrovibrating keyboard keys, and an electrovibrating palm rest. Moving forward, we discuss the medium-fidelity prototyping of the mouse pad and palm rest, where we conduct some preliminary experimentations to reinforce our initial explorations.

2.2.1 Sketching of multi-touch mouse

The idea of using electrovibration instead of a scroll wheel is derived from the initial brainstorming session discussed in Section 2.1. In our brainstorming session, we were particularly interested in exploring the potential applications of electrovibration technology in mice equipped with a capacitive strip for the scroll wheel and mice with large touch surfaces, such as the Magic Mouse (Figure 2.1). Drawing inspiration from these innovative designs, we envisioned enhancing their capabilities by incorporating electrovibration features. Our primary goal was to improve the user experience by integrating haptic feedback into various gestures.

Throughout brainstorming, we discussed how electrovibration could elevate functions like cursor movement, dragging, scrolling, and multi-touch gestures. These gestures include swiping across the mouse surface horizontally or vertically for smooth horizontal or vertical scrolling. Additionally, a single-finger horizontal swipe could allow users to navigate backward or forward in a web browser, while a two-finger horizontal swipe could enable seamless switching between apps.

One of the applications of electrovibration feedback is during scrolling activities, such as adjusting volume using the scroll wheel. This integration can mimic the tactile sensation of a mechanical scroll wheel, providing users with a constant and engaging feeling as they scroll through content.

Lastly, during zoom in/out actions, the user can experience varying haptic sensations. For example, zooming out could result in a reduction in amplitude/frequency, simulating a contraction effect, while zooming in could create an opposite sensation, giving the impression of expansion.

---

[1] https://www.amazon.ca/Apple-Magic-Mouse-Latest-Model/dp/B09BRD98T4

Figure 2.1 Magic Mouse[1]

It’s essential to consider that while many gestures can benefit from electrovibration technology, certain actions, such as double-tapping, might not be suitable for effective implementation with this haptic feedback. This is because electrovibration feedback is induced through the frictional force, which requires the sliding of a finger or a part of the hand across the surface.

After recognizing the potential added value of electrovibration in the context of the Magic Mouse, we were eager to explore the idea further by taking the next step and implementing a haptic sketch. To bring our concept to life, we developed a preliminary design for an electrovibrating mouse, as illustrated in Figures 2.2 and 2.3. Furthermore, we proceeded to create a mock-up of the electrovibrating mouse. Although the mock-up was not fully functional, it provided a tangible representation that allowed us to grasp the potential user experience.

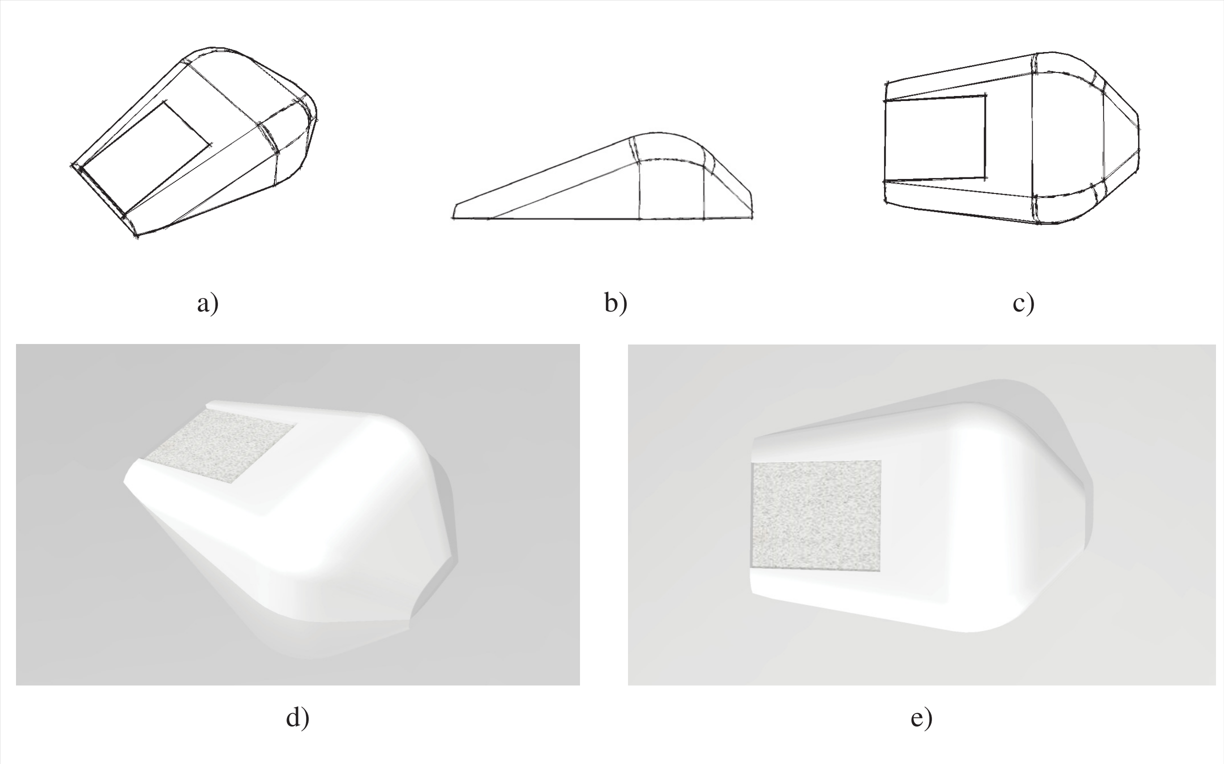

a) b) c)
d) e)

Figure 2.2 Sketches and 3D model of mouse with electrovibrating multi-touch surface. (a) Perspective view, (b) Side view, (c) Top view, (d) Actual perspective view, (e) Actual top view

The successful implementation of an electrovibrating mouse hinges on effectively integrating position sensing with electrovibration, which poses complex and challenging accuracy issues. Moreover, it’s important to acknowledge that the resulting capabilities of an electrovibrating mouse would likely overlap with those of touchscreens or touchpads, which have already been extensively explored with electrovibration technology.

Considering these factors and the need to focus on more feasible and original ideas, it was decided to discontinue the pursuit of this particular concept. While the concept still holds potential for future exploration, we chose to prioritize other ideas that we believed to be more manageable and innovative within the scope of this research.

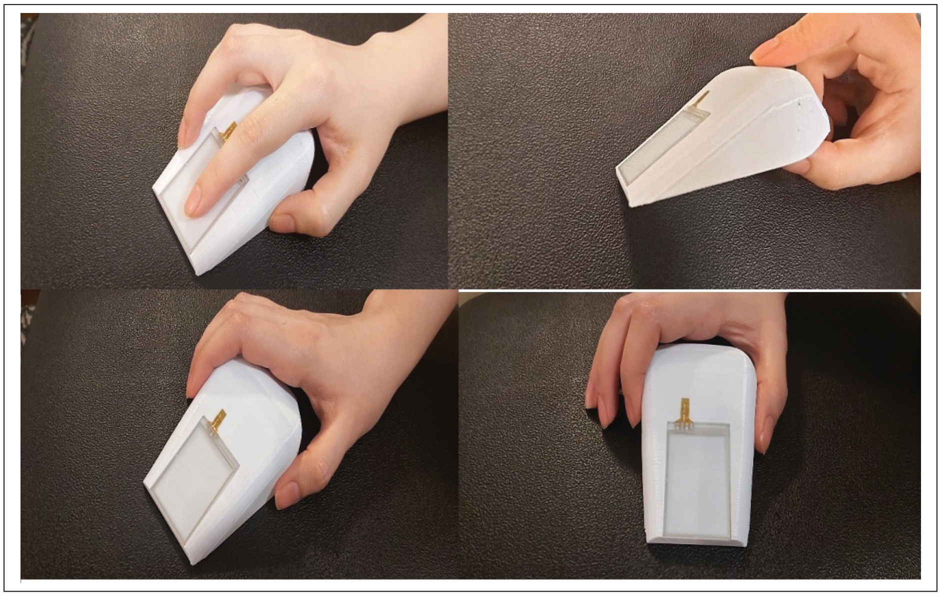


Figure 2.3 Mockup of 3D model depicting mouse surface and structure

2.2.2 Sketching of mouse pad, palm rest and keyboard keys

Building upon our earlier exploration of the electrovibrating mouse concept in the preceding section, we decided to continue our investigation by focusing on additional surfaces, including the mouse pad, palm rest, and keyboard keys.

The main objective of our exploration was to assess whether users could recognize textures on the mouse pad, palm rest, and keyboard keys accidentally or deliberately. Additionally, we aimed to investigate whether a textured key could be more easily located when compared to a standard smooth key.

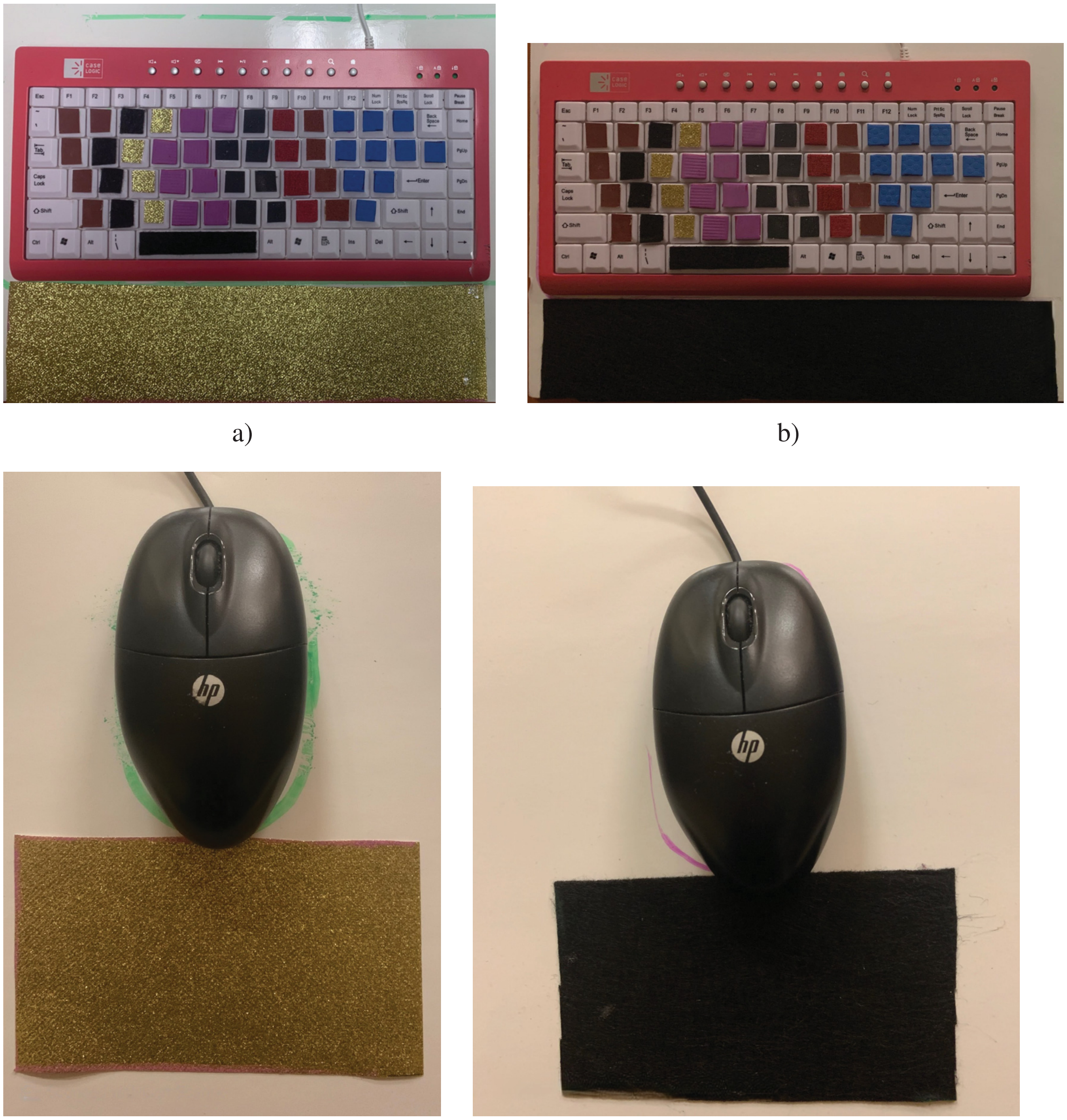
Therefore, in order to emulate the potential effects of electrovibration, we first created a haptic sketch of a palm rest, keyboard keys, and a mouse pad with textures placed at various locations. For the keyboard keys, we considered five different levels of sandpaper, ranging from 40 grit to 440 grit, as well as fabric. Each of these materials has a unique surface roughness. The materials were affixed to the keys of the keyboard, as shown in Figure 2.4. We used eight different textures to cover a wide range of fineness. For the palm rest and mouse pad, we affixed only a piece of fabric or sandpaper with 120-grit fineness, as shown in Figure 2.5.

Figure 2.4 Keyboard haptic sketch

To quickly assess the potential of integrating electrovibration into the mouse pad, palm rest, and keyboard keys surfaces, we conducted informal experimentation. Our team engaged three right-handed volunteers, including myself, my thesis supervisor professor Vincent Levesque, and three fellow members from our research lab, for this informal study.

The procedure involved having each volunteer position their thumbs over the space bar of the keyboard, while the rest of their fingers were placed on different keys. To navigate the mouse, the right hand was used. These volunteers were seated comfortably behind a desk with the haptic prototype placed before them. They were instructed to engage in typical keyboard typing and mouse usage for approximately a minute, simulating their regular activities.

During the informal experimentation, the volunteers were seated behind a desk table where the haptic sketch was placed. They were instructed to sit comfortably as they normally would and perform typing and working with a keyboard and mouse for a minute or so. Afterward, they were instructed to slide their fingertips on the keyboard keys and their palms on the resting area



a)

b)

c)

d)

Figure 2.5 Haptic sketches: a) palm rest with sandpaper 120-grit, b) palm rest with fabric cotton, c) mouse pad with sandpaper 120-grit, and d) mouse pad fabric cotton

of the keyboard and under the mouse for about a minute. The purpose of this instruction was to allow the volunteers to become familiar with the materials placed on the different surfaces and to feel the textures of each one.

Based on the volunteers' feedback, we found that sandpaper with a 40-grit range was too obvious and unpleasant, while cotton fabric on the space bar and middle keys and sandpaper with a 120-grit range provided a good balance of roughness and smoothness, leading to efficient and perceivable textures.

One interesting discovery was that volunteers could feel the textured surfaces when resting their palms on the cardboard resting area and under the mouse during normal interactions with the keyboard and mouse. The typing posture, however, also influenced the perception of texture. Volunteers who rested their palms on the palm rest throughout normal use consistently noticed the textures, while those who lifted their palms might not have experienced the same level of input.

In conclusion, the results provide promising directions for the implementation of electrovibration in user interfaces. By focusing on textures that strike a balance between roughness and smoothness, we can create more efficient and pleasant interactions between users and devices. Additionally, understanding the influence of typing posture on the perception of texture can help design ergonomic interfaces that cater to a wider range of users' preferences. Further research and refinement of these ideas could lead to the development of more intuitive and engaging electronic devices with enhanced tactile feedback through electrovibration.

2.2.3 Medium-fidelity prototyping of mouse pad and palm rest

To delve deeper into these discoveries, we have created two medium fidelity prototypes: one focusing on temporal rendering using the mouse pad and palm rest, and the other on spatial rendering using the mouse pad. These prototypes incorporate electrovibration surfaces instead of traditional textures. It is worth mentioning that at this stage of exploration, we have not included the electrovibrating keyboard keys in the prototypes, as their development poses more significant challenges.

The first prototype, which involves temporal rendering using a mouse pad and palm rest, aims to assess the impact of different signal parameters on perception. The second prototype aims to investigate whether volunteers can perceive electrovibration feedback over an extended period of a few hours, both during intentional and unintentional interactions.

These prototypes were created for informal testing, involving a small group of volunteers that included myself, my thesis supervisor Professor Vincent Levesque, and a few members of our lab.

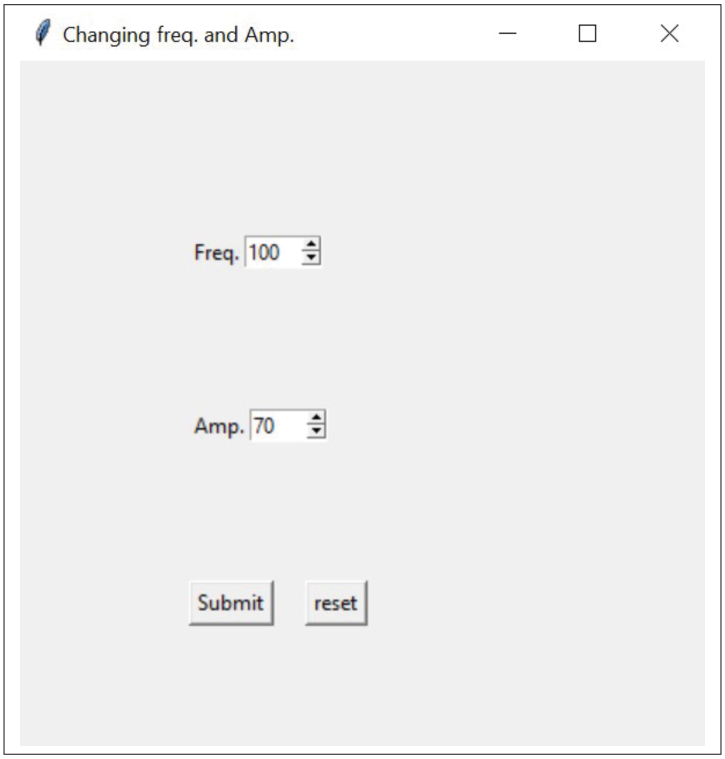
Temporal rendering with the mouse pad and palm rest

The main goal of this prototype is to investigate whether the insights gained from our previous findings (Section 2.2.2) with textures can be successfully applied to an actual electrovibration surface. Specifically, we aim to determine if volunteers can perceive and detect electrovibration feedback on the mouse pad and palm rest in a manner similar to how they perceive textures.

To investigate the hypothesis, three variations of the prototype were used, all involving the use of 3M capacitive plates positioned beneath both the mouse and keyboard. These plates were responsible for generating the electrovibration feedback.

In the first variation, we employed a signal generator to create adjustable voltage signals with varying amplitudes, frequencies, and waveform types. These signals were then amplified to drive the electrovibration plates. We determined the most perceptible sensations, considering amplitudes ranging from 100 V_{pp} to 250 V_{pp}, frequencies from 50 Hz to 10k Hz, and waveform options like sinusoidal, triangular, and square. This variation is designed to study the effects of these signal parameters on the perception of electrovibration feedback.

In the second iteration, a notable change was introduced. We replaced the conventional signal generator with a Raspberry Pi to drive the electrovibration signal. This shift allowed us to implement a graphical interface (Figure 2.6) to provide more flexibility and control. Volunteers could directly adjust frequency and amplitude values through input text boxes. The changes made in the graphical interface resulted in corresponding changes in the sensations generated by the 3M capacitive plates. After making adjustments, volunteers could apply the new frequency and amplitude settings by clicking a submit button, followed by a two-second pause to allow time for the changes to take effect. The second variation focuses on examining the perception of electrovibration feedback when a user interacts with the mouse pad through a user interface. The goal is to understand how the user's interactions with the mouse pad influence their perception of the feedback.



Freq. 100

Amp. 70

Figure 2.6 Graphical user interface for temporal rendering: second variation

For the third variation, a programmable signal similar to the one used in the second setup was used. However, this time, the electrovibration plates were enabled and disabled at random time intervals for a duration of five minutes. This addition introduced an element of unpredictability to the sensations experienced by the volunteers. The third variation explores the perception of electrovibration feedback on both the mouse pad and palm rest when volunteers interact intentionally or unintentionally with these surfaces. This prototype helps us understand how intentional and unintentional interactions affect the perception of electrovibration feedback.

Throughout our investigation, volunteers actively engaged in direct interaction with the 3M capacitive plate. Additionally, they simulated typical computer usage scenarios by working with a keyboard and mouse as they would on a PC. They explored the plate by sliding different parts of their hands and fingers across it, aiming to assess their perception and tactile feedback.

After the interactions with each variation, volunteers shared their feedback about their overall experience.

Volunteers' feedback revealed interesting insights from all three setups. Some volunteers reported that they kept their wrists raised while typing, leading to limited contact with the electrovibrating keyboard palm rest. However, volunteers who rested their palms while typing noted a more pronounced perception of electrovibration feedback at higher intensity levels, but they found it difficult to perceive at lower intensities. Additionally, since these volunteers primarily used their fingers for typing, their hands remained relatively stationary on the keyboard, resulting in a decreased sensation of electrovibration. Nevertheless, they did mention instances where they felt the electrovibration when transitioning from using the mouse and placing their hand back on the electrovibrating mouse pad. Moreover, they experienced the sensation of electrovibration when stretching their fingers to press specific keys.

Volunteers confirmed their ability to perceive the electrovibration feedback when the voltage amplitude was set to 70V. They reported a stronger perception when the voltage was increased to the maximum allowable level of 100V, indicating an upper threshold for comfortable feedback. Additionally, volunteers observed that higher voltage levels allowed them to sense different levels of frequency more distinctly. Based on these observations, the sensation of electrovibration was stronger when the amplitude was set to $150V_{pp}$ and above, combined with a frequency range of 50 Hz to 240 Hz, particularly under the mouse. However, under the keyboard, the sensation was milder.

In the third variation, The investigation revealed that changes in frequency and amplitude, while keeping other parameters constant, indeed produced discernible variations in sensations. Volunteers reported sensing different textures as they intentionally explored the surfaces with varying amplitude and frequency values. These sensations were also observed when volunteers were engaged in regular computer work, although the intensity was not as strong as during intentional exploration. Even in the absence of intentional interaction, there was a subtle sensation of electrovibration, particularly during mouse movement that involved wrist motion. Thus, the electrovibration was perceivable during typical computer usage, albeit to a lesser degree compared to intentional exploration.

These initial results demonstrate the potential of integrating electrovibration surfaces in a palm rest or mouse pad.

Spatial rendering with the mouse pad

Building upon the successful results with temporal rendering, we now aim to investigate the feasibility of achieving spatial rendering with the use of an electrovibrating mouse pad, using the mouse cursor as an input. By using the mouse cursor's position, we aim to render localized electrovibration and spatial patterns. While this concept has been extensively explored with touchscreens in previous studies (such as Bau *et al.* (2010); Israr *et al.* (2012)), to the best of our knowledge, there is no research on implementing it specifically with a mouse pad.

In this preliminary exploration, we employed a graphical interface similar to the one used in the variations of temporal rendering. The main focus of this investigation is to assess the feasibility of rendering shapes with haptic feedback on the electrovibrating mouse pad and to evaluate users' ability to perceive the edges of these shapes. Our objective is to determine whether users can effectively feel and distinguish the tactile boundaries of the rendered shapes through the electrovibrating mouse pad.

The graphical interface design features six rectangular colored shapes arranged at various distances from each other. When the mouse cursor moves from the surrounding white space to within a colored shape, the movement triggers a signal generator, activating electrovibration feedback. Each of the six colored shapes on the graphical interface canvas is assigned specific amplitude and frequency values to control the electrovibration feedback, enabling volunteers to perceive tactile sensations associated with the shapes.

The six colored shapes correspond to different combinations of amplitude and frequency values for generating various electrovibration stimuli. The amplitude values range from 70 V to 120 V in 10 V increments, while the chosen frequency range is 60 Hz to 240 Hz, with intervals of either 20 Hz or 10 Hz. Each shape represents a specific pairing of amplitude and frequency. Outside the shapes, the electrovibration is deactivated (Figure 2.7).

In this preliminary three-minute exploration, all volunteers consistently reported a clear perception of the electrovibration feedback when moving the cursor both within and outside the shapes. Volunteers report that they could detect the presence of the feedback. However, they did not specifically mention a perception of crispness or the ability to discern precise edges.

Overall, these initial test results indicate that users can perceive the electrovibration feedback on the electrovibrating mousepad and are able to detect changes in the electrovibration stimuli presented through the graphical interface with different shapes. However, volunteers had difficulty accurately distinguishing the edges of the shapes.

2.3 Conclusion

In conclusion, this chapter began with an exploration of potential integration surfaces for electrovibration in computer peripherals, using the haptic sketch as a foundational concept. After careful consideration, the focus narrowed down to three specific surfaces: the mouse pad, the area under the keyboard, and the keys of the keyboard. Subsequently, various informal tests were designed to evaluate the perceptibility of electrovibration feedback in different scenarios.

The findings revealed that electrovibration feedback was most noticeable during the transition between mouse and keyboard usage. Additionally, intentional exploration of the areas under the mouse and keyboard using either the palm or fingertips resulted in heightened perceptibility of the sensations. Given these results, we are confident in the efficacy of this approach.

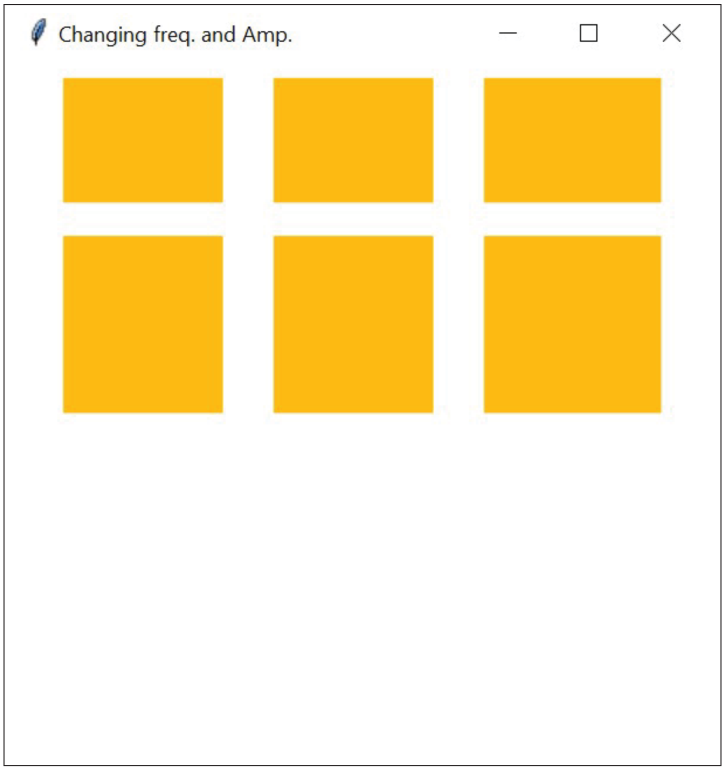


Figure 2.7 Graphical user interface for spatial rendering: preliminary exploration

Building upon these insights, the primary goal for the subsequent chapters is to design an electrovibration system specifically tailored for three target areas: on mouse pad, on the keyboard keys, and on the palm rest. These areas will be further evaluated to determine whether users can perceive electrovibration feedback when interacting intentionally or unintentionally.

CHAPTER 3

PROTOTYPE DEVELOPMENT

In this chapter, we will describe the functional prototypes designed to test the ideas presented in the previous chapters, which highlighted three surfaces as the most promising options. These prototypes incorporate a combination of hardware and software components, with a specific focus on the electrovibrating palm rest, the electrovibrating mouse pad, and electrovibrating keyboard keys.

To begin, we will outline the development of the signal generating system, which is a shared component across all electrovibrating surfaces being investigated. This component is responsible for generating programmable signals that are essential for producing the desired haptic feedback. Following the explanation of the signal generating system, we will proceed to describe each specific surface of computer peripherals individually. For each surface, we will discuss the unique hardware system employed to integrate electrovibration technology and provide enhanced haptic feedback. Lastly, we will describe the software architecture, which, in conjunction with the hardware infrastructure, enables the control, activation, and deactivation of the electrovibration surfaces.

An overview of the prototypes is illustrated in Figures 3.1 and 3.2.

3.1 Signal generating system

In order to generate the electrovibration signal, the following components are required:

Raspberry Pi with a AD/DA high-precision board: The prototypes use a Raspberry Pi, a small, single-board computer, to generate a programmable signal that controls the amplitude, frequency, and waveform of the electrovibration signal. Our prototypes were developed using the Raspberry Pi 3 Model B+ (2018) running Raspbian OS based on the Debian Linux distribution. The Raspberry Pi is connected to High-Precision AD/DA Board having Onboard ADS1256, an 8-channel 24-bit high-precision Analog-to-Digital Converter (ADC) with 4 channels supporting

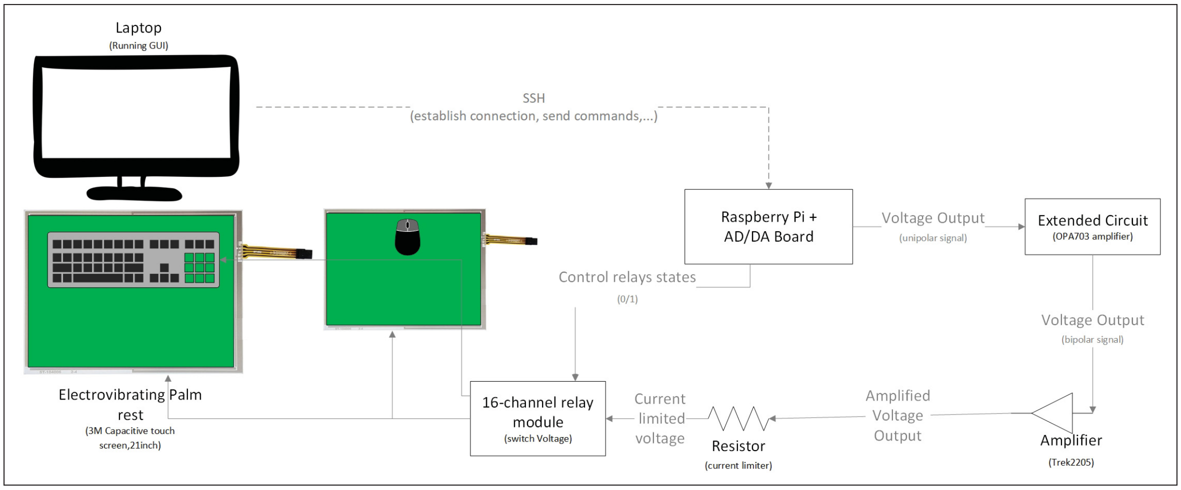


Figure 3.1 An overview of the prototypes hardware components, highlighting the electrovibrating surfaces represented by the green areas

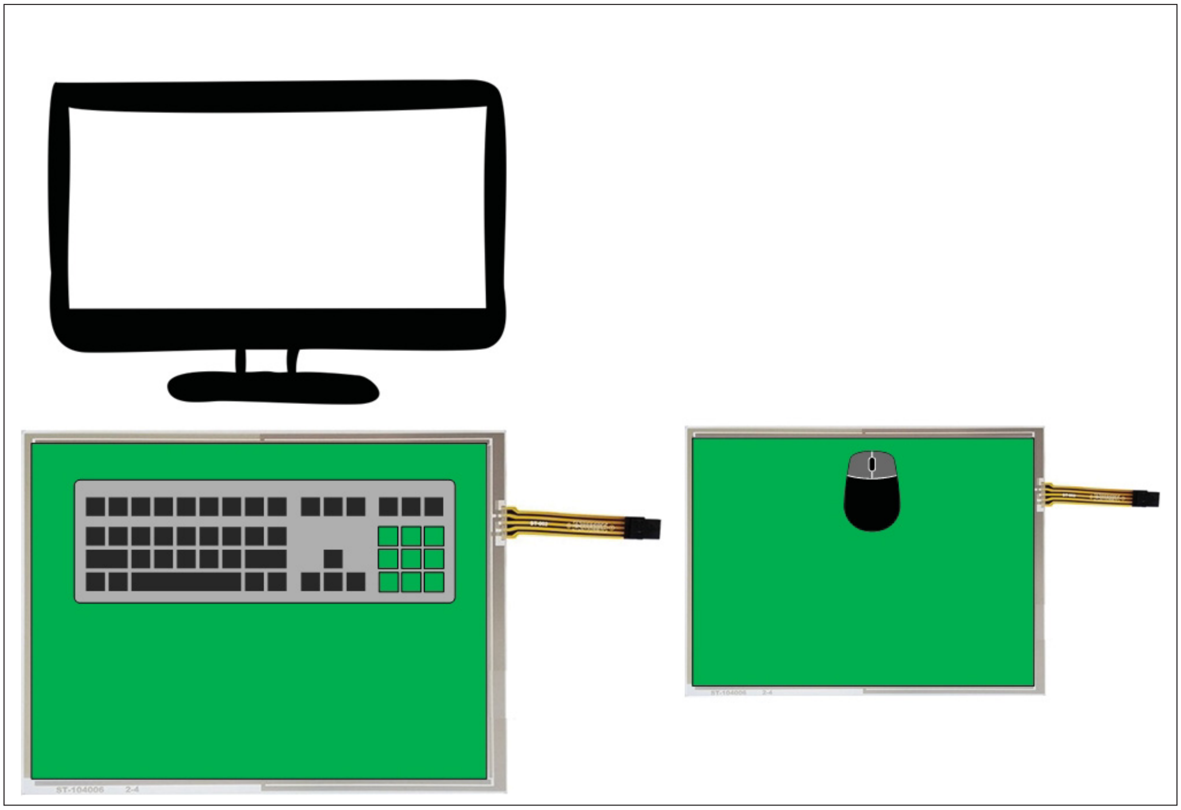


Figure 3.2 Electrovibrating surfaces prototypes: highlighted in green

differential input, and a DAC8552, a 2-channel 16-bit high-precision Digital-to-Analog Converter (DAC) (Figure 3.3). To produce an analog signal, we used one of the channels of the DAC8552 to convert the digital signal generated by the Raspberry Pi into an analog signal. The maximum amplitude of the analog signal is 3.3V, and the maximum current is 16mA. The output of this board provides a unipolar analog signal.

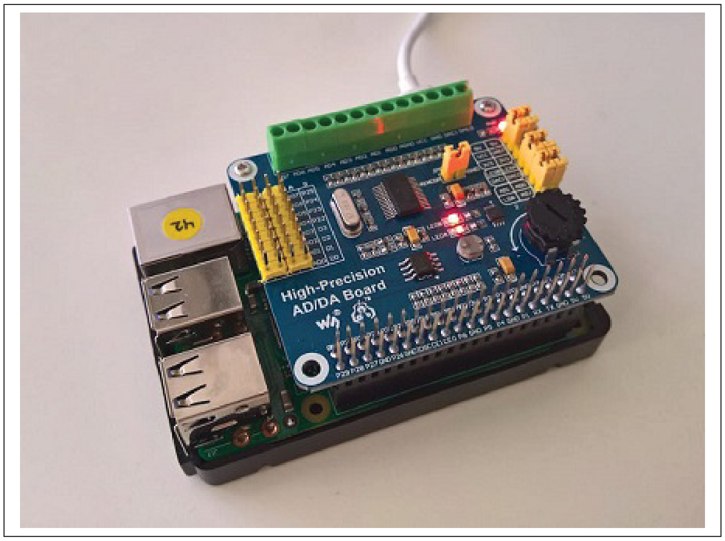


Figure 3.3 Raspberry Pi with AD/DA board [1]

Extended circuit to generate bipolar signal: In order to generate a stronger electrovibration signal, an amplifier can be used to create a bipolar signal (refer to Section 1.3). A bipolar signal has both positive and negative components.

The OPA703 amplifier is a popular choice for generating bipolar signals. This amplifier features high bandwidth, low distortion, and low noise, making it ideal for use in electrovibration applications. The OPA703 is capable of generating a bipolar signal with high precision and accuracy. The extended circuit shown in Figure 3.4 is derived from the research conducted by Friaa *et al.* (2022) and uses the OPA703 amplifier. This circuit operates on a +5 V supply voltage provided by the Raspberry Pi with a DAC8552. As mentioned earlier, the DAC8552

---

[1] https://www.hackster.io/laserbrain/raspberry-pi-ad-da-board-library-for-window-10-iot-core-c8cc34

produces +3.3 V analog voltage, which serves as the reference voltage for the OPA703 amplifier. As a result, the OPA703 amplifier outputs a range of ±3.3 V.

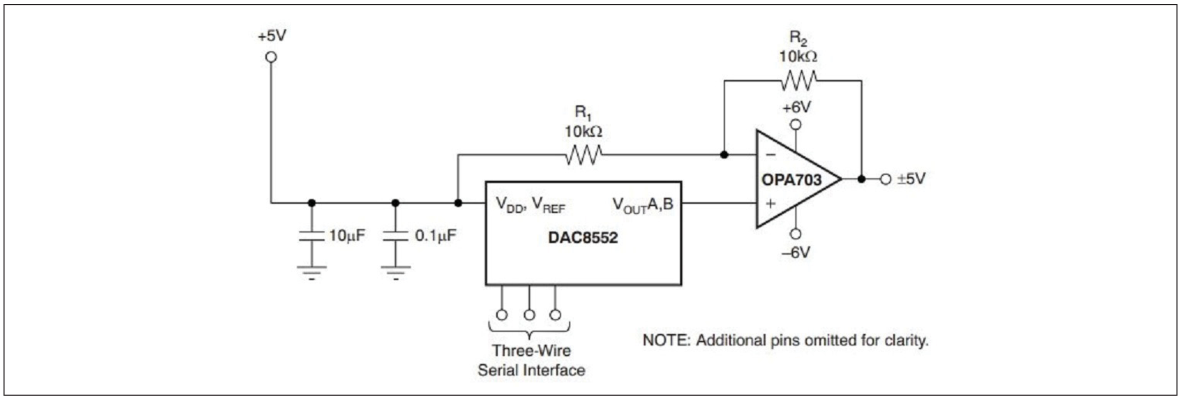


Figure 3.4 The extended circuit employed in the prototype to generate a bipolar output using DAC8552 [2]

High-voltage amplifier: The output signal from the previous stage is connected to a Trek 2205 high-voltage amplifier. This amplifier has an input voltage range of 0 to ±10 V DC or peak AC[3]. Its purpose is to amplify the generated signal to a level that is suitable for producing the desired tactile sensations. With a gain of 50 V/V DC, the Trek 2205 amplifier can generate an output ranging from 0 to ±500 V DC or peak AC. When a maximum input voltage of ±3.3 V is applied to this high voltage amplifier, which is obtained from previous circuit, the amplifier's output reaches a maximum of ±165 V or 330 V_{pp}.

Current-limiting resistor: It is important to ensure the safety of the user and to prevent any potential damage to the circuit. Therefore, a resistor is added to limit the current to less than or equal to 5mA based on Ohm's Law (I = V/R). For example, considering that the maximum voltage used is 200 V, using a 40 kΩ resistor will result in a current of 5 mA, which remains within the safe range. Similarly, for a given amplitude of 100 V, the current with a 40 kΩ resistor will be 2.5 mA, which is also within the safe limits.

---

[2] https ://www.ti.com/lit/ds/symlink/dac8552.pdf

[3] https://esdvietnam.com/storage/files/$UK_{T}RK_{2}205_{D}S$.pdf

Relay module: A relay module (Figure 3.5) controls high voltage or current devices with low voltage signals. It has 8 channels that can switch independently to control up to 8 devices. It runs on a 5V power supply, obtained from a microcontroller or Raspberry Pi. The relay channels are controlled by low-level signals like digital output pins from the Raspberry Pi.

It is important to note that many electronic components are not designed to handle high voltages, which significantly restricts the available options. Consequently, finding a suitable solution proved to be a challenging task.

To connect the relay module board to the Raspberry Pi, we made several connections. First, the VCC pin of the relay module board should be connected to the 5V pin of the Raspberry Pi, while the GND pin of the relay module board should be connected to a ground pin on the Pi. Finally, each of the control pins of the relays should be connected to separate GPIO pins on the Raspberry Pi. The overview of the prototypes' hardware components is illustrated in Figure 3.6.

In this particular case, the goal is to connect the relay to 11 electrovibrating surfaces that will be described in Sections 3.2.1 and 3.2.2. This requires a total of 11 switches, which can be accomplished by coupling two 8-channel relay module boards.

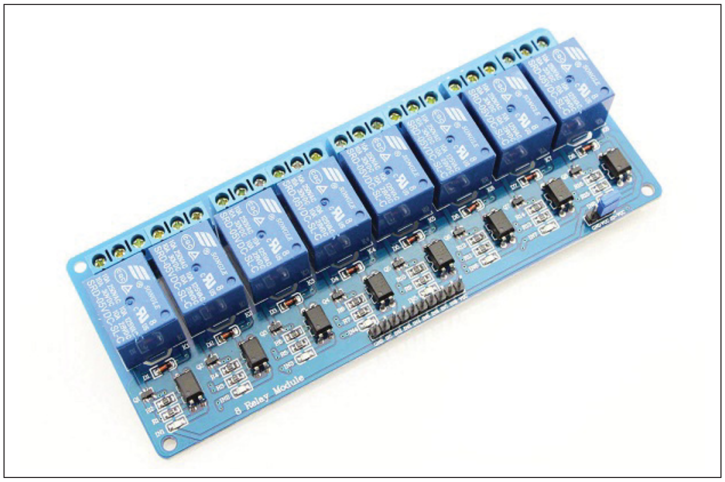


Figure 3.5 5V 8-Channel Relay interface board [4]

---

[4] https://www.amazon.ca/SainSmart-101-70-102-8-Channel-Relay-Module/dp/B0057OC5WK?th=1

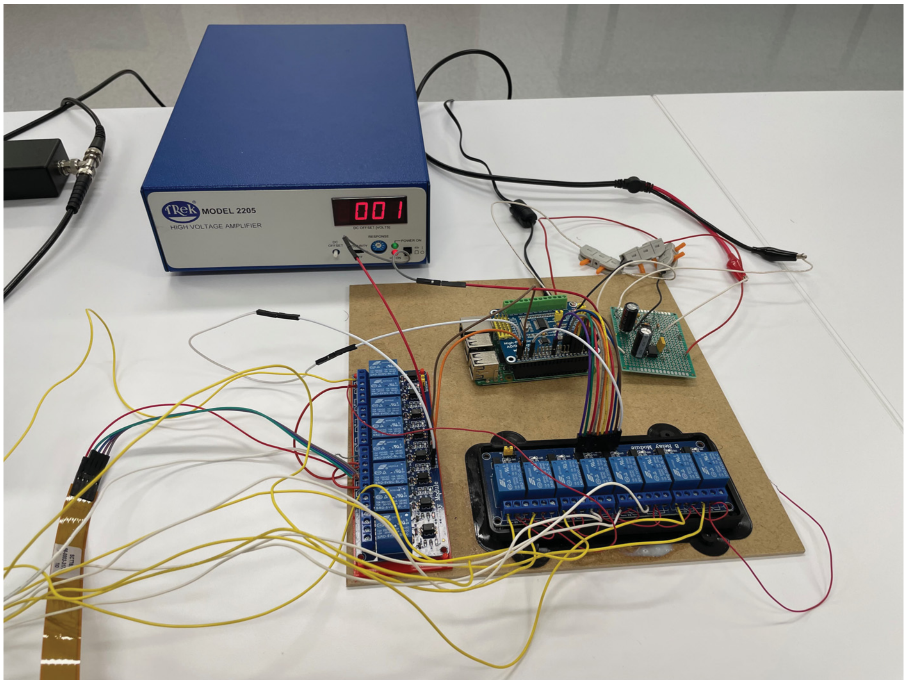


Figure 3.6 An overview of the prototypes' hardware components

Current-limiting wrist strap: The digital ground of the circuit is connected to a bracelet with a built-in resistor (Figure 3.7). This will be connected to the wrist of the user to dissipate current leakage in case of short circuit, protect the system from static charge and create stronger electrovibration sensation on electrovibrating surfaces. The built-in resistor will reduce the current to the range of μA, therefore lowering the risk of a shock.

Several studies have made use of similar wrist straps. In one study (Osgouei *et al.*, 2019), an anti-static wristband with a 1 MΩ resistor was worn by volunteers to maintain a safe electrical environment during experiments and prevent excessive current flow through their bodies. Another study (Ryu *et al.*, 2018) used an adjustable wristband with a 1 MΩ resistor for proper grounding while evaluating the effect of mechanical vibration on the perception of electrovibration. Similarly, in Bau *et al.* (2010), researchers employed an antistatic wristband to establish a return ground path for the signal, leading to increased tactile sensation for users. The use of the wristband allowed for safe and effective grounding during the experiments, leading to enhanced tactile feedback with electrovibration.

Figure 3.7 Anti-static wrist strap [5]

Oscilloscope: We use an oscilloscope to measure the signal's amplitude, frequency, and waveform. The oscilloscope is connected to the output of the 40 kΩ resistor to display the resulting output signal.

3.2 Electrovibrating surfaces

SCT3250 capacitive plate and custom-made surfaces: To create an electrovibration display for the palm rest and mouse pad, a capacitive touch panel (MicroTouch SCT3250, 3M) is employed. This touch panel comprises a transparent conductive layer coated with a thin insulator atop a thick glass plate. Applying a high voltage waveform (around 200 V_{pp}) to the conductor and electrically grounding the human body modulates the friction between the sliding finger and the touch panel. Acting as a capacitive touch sensor, the SCT3250 plate is responsive to human touch, detecting changes in capacitance caused by the presence or absence of a finger. In the current circuit, the capacitive plate is used to generate the electrovibration sensation, allowing the participant to perceive the applied signal through tactile feedback (Figure 3.8).

---

[5] https://www.ioniser-pro.co.uk/ioniser-pro-wrist-strap/

[6] https://lcdquote.com/17-8721-203-01/

Figure 3.8 3M capacitive touchpanel [6]

3.2.1 Electrovibrating palm rest and electrovibrating mouse pad

For this purpose, we are using a 21″ 3M capacitive plate (Figure 3.9) placed right below the keyboard. In other work, Friaa *et al.* (2022) took a different route by combining a commercial keyboard (Logitech K380) with two smaller capacitive plates. Unlike Friaa's approach, where two separate plates were used, we've chosen a single, larger capacitive plate. This means there's no gap between plates, resulting in a smoother experience.

The electrovibrating mouse pad works on the same principle as the electrovibrating palm rest, but it incorporates a 15.58″ 3M capacitive plate (Figure 3.10) underneath the mouse, serving as the mouse pad.

In order to generate voltage signals that create tactile sensations on electrovibrating mouse pad and electrovibrating palm rest, specific values were carefully chosen. These values include using a sinusoidal waveform, an amplitude of 200 volts peak-to-peak (V_{pp}), and a frequency of 80 Hz. The selection of these waveform characteristics was done with the intention of maximizing the distinguishability of the haptic sensations that users would experience.

Figure 3.9 Electrovibrating palm rest

The frequency value is obtained from Section 1.3, where we delved into the impact of amplitude and frequency on perception. Additionally, we maintained a consistent amplitude with the work of Friaa *et al.* (2022), who used ±100V.

Furthermore, our selection of these values was reinforced by the outcomes of our preliminary experiments in temporal and spatial rendering, detailed in Section 2.2.3. These experiments demonstrated that these specific values offer optimal results.

3.2.2 Electrovibrating keyboard keys

To fabricate the electrovibrating keyboard keys (Figure 3.11), we selected a Dell wired keyboard (KB216) with flat keys to minimize the masking effect caused by wobbling, which could distort the electrovibration sensation. The flat surface of the keys ensures smooth and consistent sliding, making it easier to incorporate electrovibration effectively. Additionally, this keyboard's shorter keys compared to other mechanical keyboards prevent wobbling during typing.

Figure 3.10 Electrovibrating mouse pad

Figure 3.11 Electrovibrating keyboard keys

The electrovibrating keyboard keys are composed of several segments, including the keys themselves, a conductive plate and electrical insulator, and wires attached to the conductive plate.

Keys

Preliminary efforts were made to design 3D models of keys (Figure 3.12), including those for the numeric keypad with a total of 9 keys, that closely resembled those of the original keyboard. The intent was to cast these models in metal and subsequently apply an insulator coating. The dimensions of the keycap and key switch were obtained from online sources and measured. Then, using design software such as Fusion 360 and AutoCAD, a few different 3D models of keys were created, and the .stl file was printed using a 3D printer. Figure 3.13 illustrates some of the 3D model designs we created using this software.

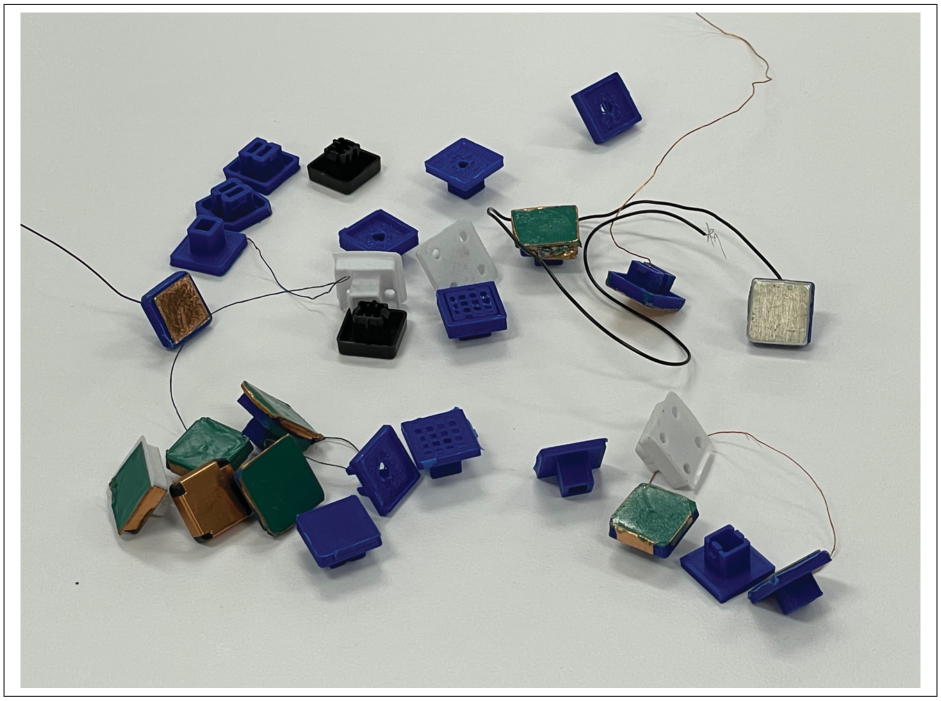
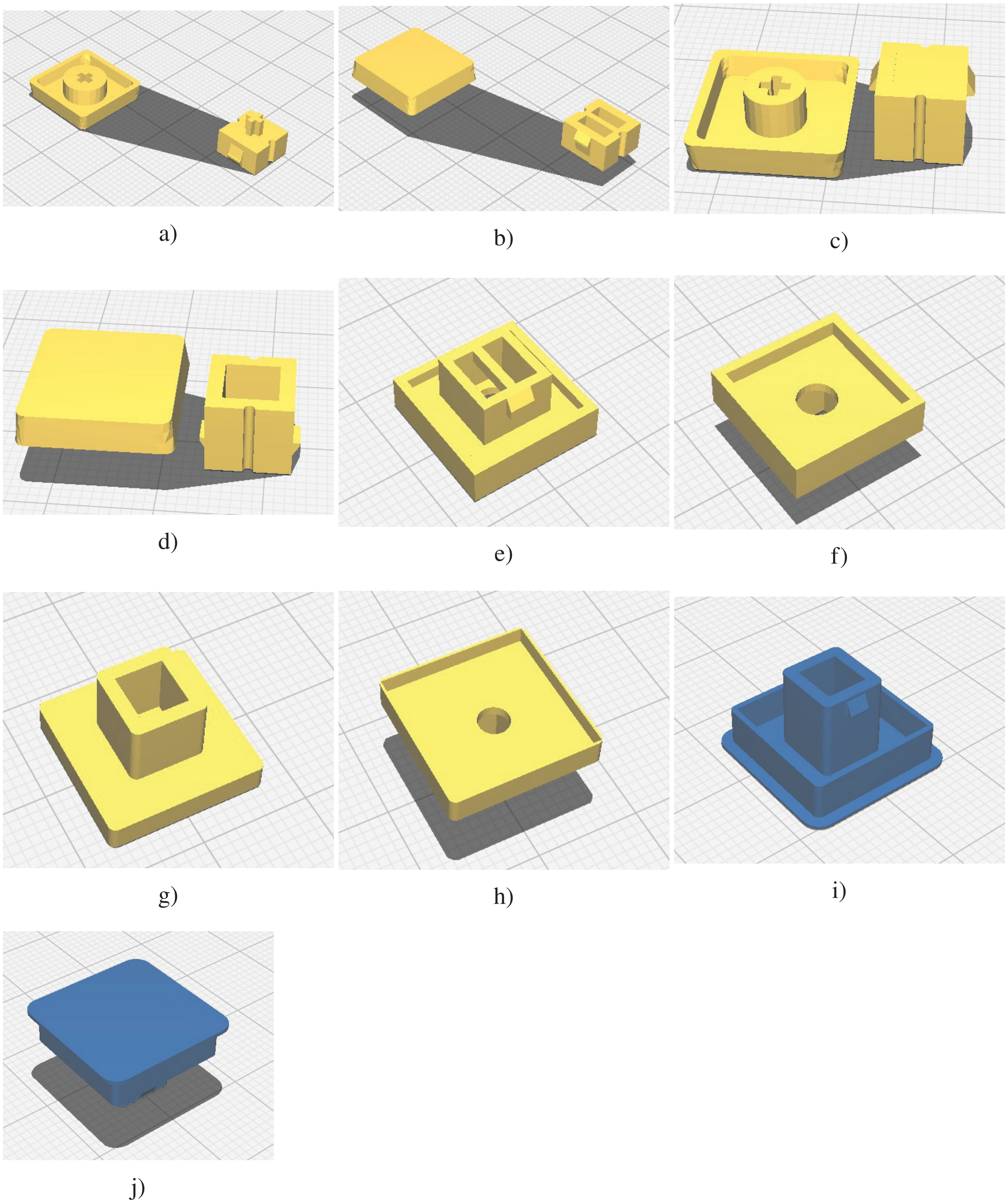


Figure 3.12 3D-printed keyboard keys



a)

b)

c)

d)

e)

f)

g)

h)

i)

j)

Figure 3.13 Keyboard keys 3D designs: (a) and (b) depict the bottom and top of the key respectively, (c) and (d) the bottom and top of the key respectively, and so on

However, after placing these 3D-printed keys in the keyboard frame, it became apparent that there were many issues with their design. Firstly, the 3D printer was not entirely accurate, with some errors occurring in dimensions particularly within the millimeter accuracy range. This led to the 3D-printed keys not being the same size as the manufactured keys, causing wobbling, difficulties fitting into the keyboard frame, keys not being as smooth or stuck in the slot, and other problems.

We decided to opt for a different solution by adding an electrovibrating surface on top of the manufacturer's keys. By using the existing keys as a base for the electrovibrating surface, we can avoid the challenges associated with custom-made keys, such as potential wobbling issues. However, it's worth noting that this solution might raise the height of the keys slightly, which could lead to the possibility of fingers getting stuck when sliding from left to right. Despite this drawback, using the manufacturer's keys offers the advantage of a more stable platform, ensuring a consistent and constant perception of the electrovibration feedback.

Conductive material and electrical insulator

The development of electrovibrating surfaces for keycaps involves two critical steps: adding a conductive layer and insulating the electrode with a thin dielectric layer. We explored various conductive materials and tested them in order to verify their effectiveness to be used on keys.

We initially opted to use copper foil tape with an electrically conductive acrylic adhesive as a flexible material for our application (Figure 3.14). The tape has a thickness of 0.066 mm and is equipped with conductive adhesive, which makes it suitable for affixing on top of the keys. With an electrical resistance of 0.005 $\Omega/inch^2$, it exhibits good conductivity for our purposes. To evaluate its conductivity, we conducted tests using a multimeter, checking the connectivity between two points on the copper tape. The multimeter consistently indicated conductivity. However, upon examining the adhesive part, we discovered that the conductive adhesive exhibited intermittent connectivity, leading to inconsistent results. Furthermore, the copper tape's surface was not as smooth as desired, introducing irregularities that masked the electrovibration sensation. Additionally, the tape was prone to tearing under pressure. Considering these factors, we decided against using the copper tape in our project.

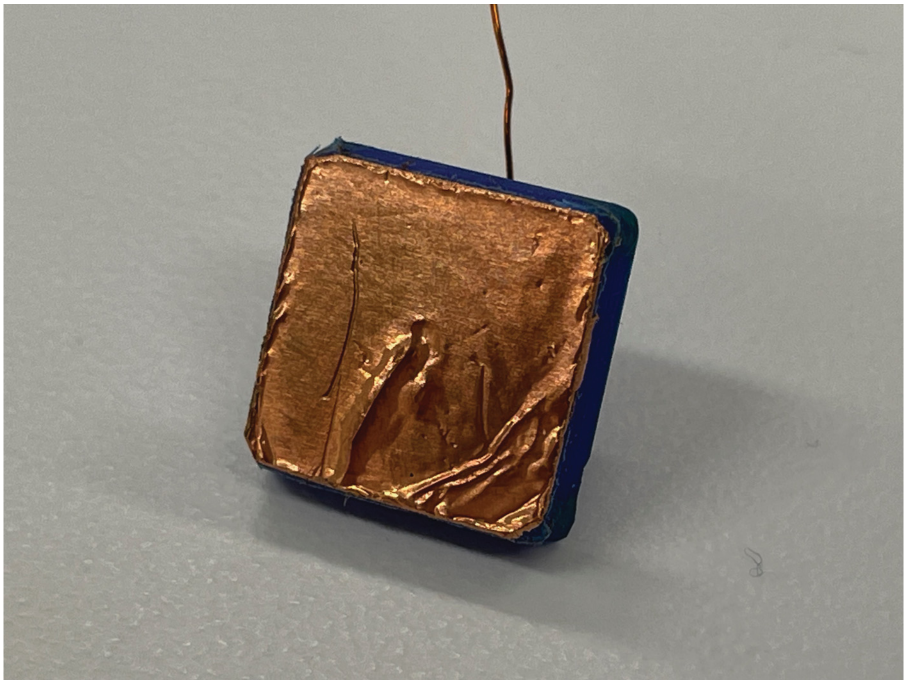


Figure 3.14 Creating keyboard key using copper foil tape (the central deformation line results from the wire positioned beneath the tape)

Secondly, we decided to test the conductivity of Bare Conductive's Electric Paint by applying it to a cardboard surface and using a paintbrush. The Electric Paint has a surface resistivity of 55 Ω/Sq at a thickness of 50 microns. However, despite our efforts, the painted surface did not exhibit any conductivity. As a result, we chose not to proceed with connecting it to a power supply. It's important to note that Electric Paint's conductivity is highly dependent on the surface it is applied to and the application method, and in this particular case, further troubleshooting may be required to understand the lack of conductivity on the cardboard surface.

Thirdly, we decided to explore an alternative method to achieve a customized conductive surface by employing a rigid conductive layer. To test its effectiveness, we obtained conductive aluminum plates of varying thicknesses: 1 mm, 1.25 mm, and 0.5 mm. We found that the conductivity of each sheet was consistent on both sides, and the sheets exhibited a sturdy structure that resisted deformation under pressure. However, we faced a concern regarding the thickness of the aluminum sheet, as it could potentially disrupt the balance of the keyboard keys. After considering this factor, we opted for the 0.5 mm thickness aluminum sheet, maintaining the desired keyboard key height (Figure 3.15).

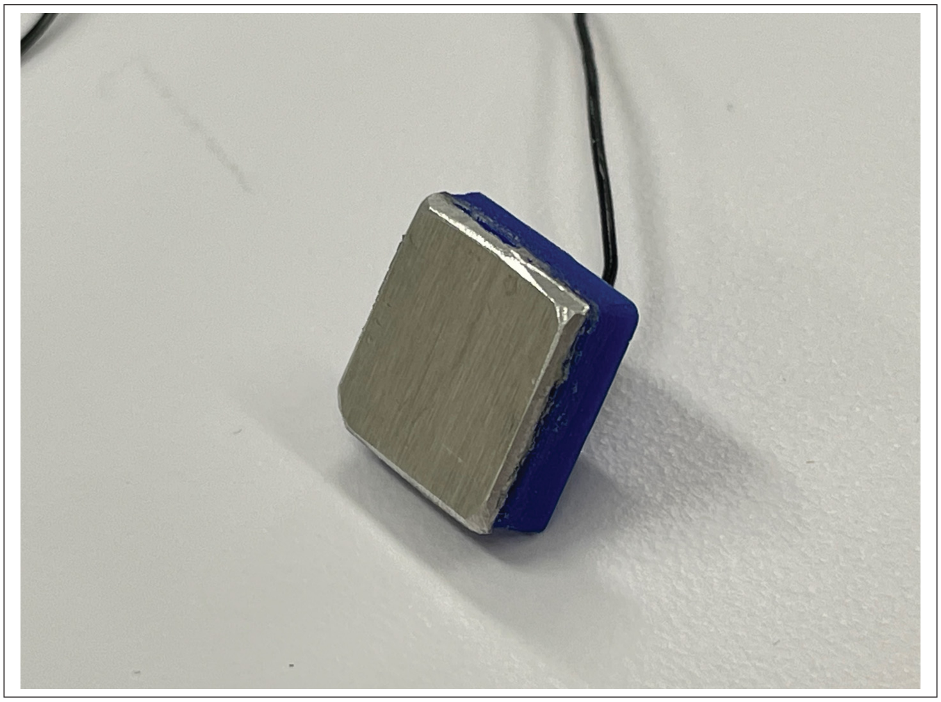


Figure 3.15 Creating keyboard key using aluminum plate

In order to finalize the fabrication of our customized electrovibration keys, we needed to introduce a dielectric layer on top of the conductive layer. The dielectric layer should possess a thin and optimal thickness, striking a balance between not being too thick to impede the absorption of opposite charges and not being too thin to allow current to pass through it. Two common methods of obtaining the dielectric layer are through the application of a thin layer of varnish or spray paint. The dielectric constant and thickness of the insulator are crucial design factors that can significantly influence the tactile sensation experienced (Bau *et al.*, 2012).

We employed Sprayon's EL609 green insulating varnish (Figure 3.16) as a means of insulating the aluminum plates. In order to achieve an adequate thickness for the insulating layer, we applied two coats of paint. In our first attempt, the plate was subjected to a voltage of 100 V and a frequency of 100 Hz, targeting stimulation of the fingertip. Despite gradually increasing the voltage to 200 V, no electrovibration sensation was perceived from the plate. In a subsequent trial, we modified the approach by applying only one coat of paint. This time, we applied a voltage of 100 V and gradually increased it until reaching 200 V. It was at approximately 150 V that we were able to detect electrovibrations when sliding our finger across the plate.

Figure 3.16 EL609 green insulating varnish

Wires

To establish connectivity between the conductive layer of the key and the overall prototype in our electrovibrating key setup, we use wires. These wires link the conductive layer to the signal generator responsible for tactile feedback. These wires need to be extremely thin and, consequently, fragile to enable their integration within the key mechanism. Despite their fragility, they must be robust enough to withstand the key's movement and maintain a reliable connection throughout its operation.

A notable consideration is that the wires are threaded through the keyboard frame, necessitating their ultra-thin nature. To address this requirement, we decided to employ headphone cables.

Once we gathered all the trial results, the fabrication of the electrovibrating keys commenced. Using a hacksaw, we cut aluminum sheets to match the length and width of each key. Subsequently, we employed a sander bench grinder along with multiple sandpapers of varying grit levels, ranging from fine to coarse, to round the edges, achieving a smooth finish. For insulation, we coated the aluminum sheets with a single layer of insulating varnish. With precision and care, we spray-painted the sheets by holding the spray can at a diagonal angle, approximately 10 inches away from the surface. Applying gentle pressure on the nozzle, we ensured an even and uniform coating across the entire plate. Following this, we soldered the end of each headphone wire and securely attached them to the aluminum sheets using conductive adhesive. We then passed the wires through the keyboard frame and connected them to the signal generator system.

Figure 3.17 depicts the system setup, showcasing the electrovibrating palm rest, electrovibrating mouse pad, and the electrovibrating keyboard keys.

3.3 Software architecture

The third part of the prototype system is the software architecture.

The software architecture serves as an interactive application on a PC, with corresponding firmware running on the Raspberry Pi. It enables the activation or deactivation of electrovibration feedback according to the experimental protocols which will be introduced in the next chapter. On the PC, the software establishes an SSH connection with the Raspberry Pi's frequency generator library implemented on Raspbian. Through this connection, it sends commands containing frequency, voltage, and waveform data as inputs. The frequency generator library on the Raspberry Pi processes these commands and triggers the corresponding GPIO pin to generate a signal. We chose to implement the interactive application on a PC instead of directly on the Raspberry Pi due to performance issues observed during our preliminary experimentations with a medium-fidelity prototype (Section 2.2.3). The PC's higher processing power and memory capacity can help eliminate the observed lag.

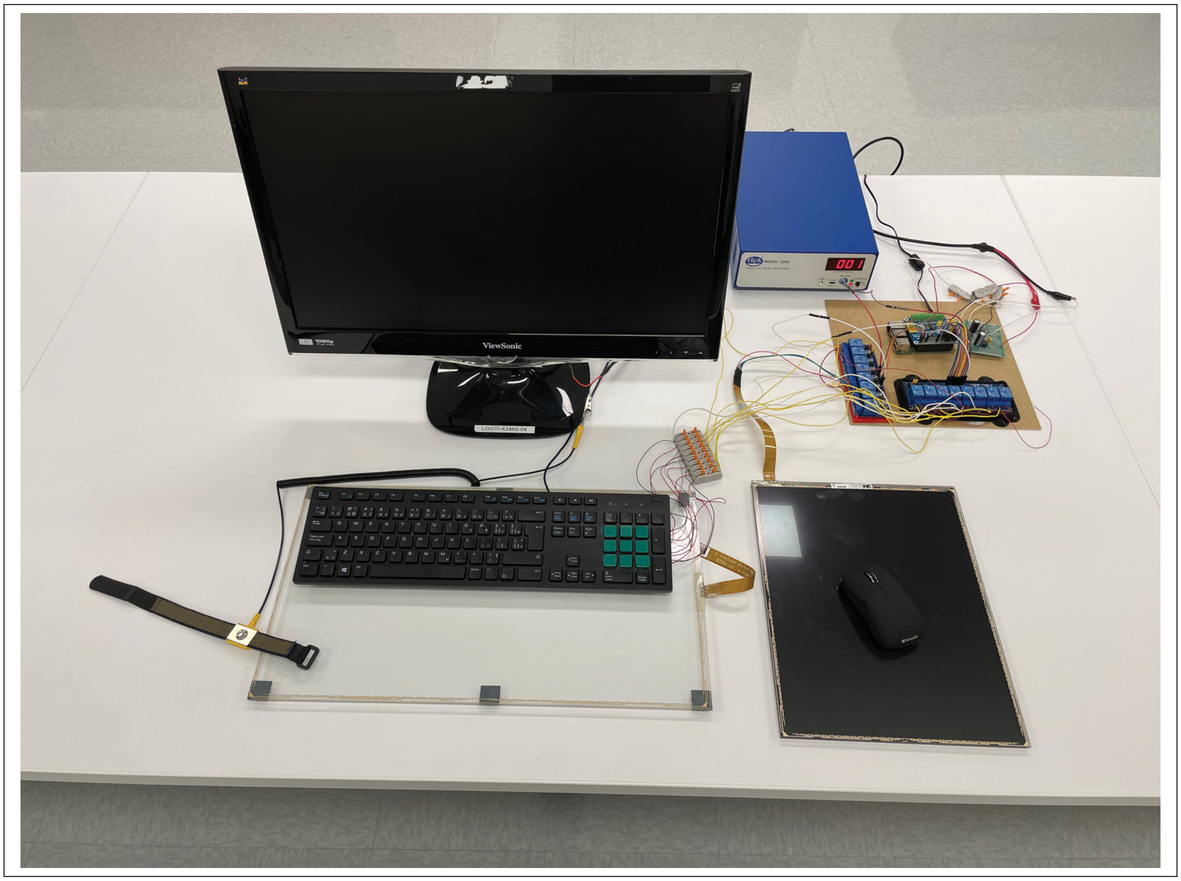


Figure 3.17 Hardware setup: electrovibrating palm rest, mouse pad, keyboard keys, and signal generator

The software architecture consists of several components: a network communication, a frequency generator library implemented on a Raspberry Pi, and a main class implemented on the PC interface. These components work together to enable the PC interface to remotely control the frequency generator library on the Raspberry Pi through the secure SSH connection.

Network communication

The PC interface on the desktop computer communicates with the Raspberry Pi through an SSH connection, which serves as a way to establish network communication. By using SSH, we can remotely log into the Raspberry Pi's command prompt and execute commands. This method of connection was chosen for its simplicity and efficiency, primarily due to the availability of a straightforward python library that facilitates fast connection establishment and communication. Additionally, SSH ensures minimal delay in command transmission once the connection is established.

Frequency generator library

We have developed a Python library on Raspberry Pi that enables the generation and playback of sinusoidal waveforms with specific frequencies and amplitudes. This library communicates with the PC interface implemented on the desktop computer. Whenever a request is sent from the PC interface, the library generates the corresponding sinusoidal waveform. It then establishes a connection with the GPIO pins of the Raspberry Pi and a relay module to activate them, ensuring that the generated waveform is output through the appropriate channels. We are using GPIO pins 14, 15, 18, 2, 25, 3, 27, 22, and 26 of the Raspberry Pi to output the voltage.

PC interface

The PC interface is a software application designed for desktop computers, developed in python. It features a main class responsible for overseeing and coordinating key functionalities. One of its main roles is to handle communication with the frequency generator library on the Raspberry Pi. This involves establishing a connection and transmitting input parameters like frequency, amplitude, and waveform to the frequency generator library. Additionally, the main class facilitates communication with an Excel file using the openpyxl library, enabling it to record participant inputs into the spreadsheet. The result is an interactive interface.

3.4 Conclusion

In this chapter, we detail the development of functional prototypes aimed at testing our proposed electrovibrating surfaces. These prototypes include an electrovibrating palm rest, electrovibrating mouse pad, and electrovibrating keyboard keys. The signal generating system, an important component shared across all surfaces, is introduced, involving a Raspberry Pi with an AD/DA high-precision board to produce programmable signals. The hardware and software components of each specific surface are explained, along with the role of a relay module, high-voltage amplifier, and current-limiting wrist strap in maintaining safety. For the electrovibrating keyboard keys, we describe the process of creating the customized conductive and insulating layers, as well as the integration of wires. The software architecture involves network communication, a frequency generator library on the Raspberry Pi, and a PC interface to remotely control the electrovibration feedback.

Overall, the development of the functional prototypes and the accompanying software architecture paves the way for conducting experiments to evaluate the effectiveness and user experience of the electrovibrating surfaces which will be discussed in the next chapter.

CHAPTER 4

EXPERIMENTAL DESIGN

In Chapter 2, we identified three promising surfaces for the application of electrovibration in PC peripherals: the palm rest, mouse pad, and keyboard keys. Building upon these findings, Chapter 3 focused on designing functional prototypes for these surfaces. Now, our objective is to develop experimental protocols for the three electrovibrating surfaces that will enable us to conduct a formal evaluation of these concepts. It's important to note that the software necessary for conducting these experiments has been implemented in Chapter 3.

The experiments aim to investigate whether participants can sense electrovibration feedback underneath their palms and fingertips when they come into contact with the electrovibrating surfaces by accident while performing tasks like typing on a keyboard or using a mouse, as well as when they deliberately rub their palms and/or fingertips against the electrovibrating surfaces. In the remainder of the chapter, the former will be referred to as *accidental interactions*, and the latter will be referred to as *deliberate interactions*.

Our first hypothesis is that participants can detect electrovibration feedback on all three electrovibrating surfaces during deliberate interactions. In contrast, our second hypothesis is that participants can perceive electrovibration feedback during accidental interactions, such as while typing on a keyboard or using a mouse to interact with a PC interface, but only under certain conditions. This may occur when there is increased contact with the electrovibrating surface, for example, when there is significant mouse movement over an electrovibrating mouse pad or when the user has to move back and forth between the keyboard and the mouse while utilizing an electrovibrating palm rest.

This Chapter consists of three sections. Section 4.1 focuses on the methodology, providing an overview of the three experiments that will be conducted. Sections 4.2, 4.3, and 4.4 then present the experimental protocols specific to each electrovibrating surface. These sections cover accidental interactions and deliberate interactions experiments, with detailed descriptions of the procedures involved in each case.

4.1 Methodology

The objective of our study is to determine whether participants can perceive electrovibration feedback when interacting with electrovibrating surfaces, both accidentally and deliberately. To assess the perception of electrovibration feedback in each interaction type, participants are asked to indicate whether they perceive the feedback while performing typical PC interactions tasks.

We designed three experiments to be conducted using the prototypes developed in the previous chapter. These experiments involve respectively an electrovibrating palm rest, an electrovibrating mouse pad, and electrovibrating keyboard keys. Each experiment consists of two parts: an accidental detection test focusing on the perception of electrovibration during accidental interactions, and a deliberate detection test focusing on the perception of electrovibration during deliberate interactions.

The three experiments are designed to be conducted as part of a single experimental session that lasts approximately 90 minutes. The order in which participants engage in the experiments (1, 2, and 3) is randomized. As a result, there are six possible experiment orders. It should also be noted that the order of the tests (deliberate detection and accidental detection) within each experiment is fixed, with accidental detection always first. This decision was made to prevent participants, who are naive and untrained in electrovibration feedback, from paying excessive attention to the electrovibrating surfaces during the first test (accidental detection test). Reversing the order could lead participants to focus on their hand position and potentially influence their utilization of it during the accidental detection test.

In Chapter 3, we provided comprehensive explanations of the prototypes employed. To summarize, we use a 21″ 3M capacitive plate as an electrovibrating palm rest beneath the keyboard. Additionally, a 15.68″ 3M capacitive plate is positioned under the mouse as an electrovibrating mouse pad. To enable electrovibration for the keyboard keys, we have developed a numeric keypad with nine custom-designed electrovibrating keys.

We include participants with diverse characteristics such as age, gender, and prior experience with computer peripherals, with the aim of creating a sample that is representative of a broader population, thereby minimizing any potential influence of these factors on the results obtained from the participants.

To avoid any discomfort or fatigue associated with prolonged use of the electrovibrating surface, we limit the participants' exposure to it by keeping the duration of the tasks on the computer interface relatively short and also adding a short break between each experiment.

Also, we record the participants' hand posture using a video camera to better understand when people are touching the surface, as well as to see what strategies participants are employing to complete the tasks. The video camera is positioned on the side of the workspace to capture a clear view of the participants' hands and interactions with the electrovibrating surface during the experiments.

To ensure control over the experiments, certain conditions were chosen, focusing on one level of frequency, voltage, and shape of the waveform. In all experiments, the waveform shape remains sinusoidal. However, for experiments 4.3 and 4.2, we used a frequency of 80 Hz and a voltage of 200 V_{pp}. In contrast, for experiment 4.4, we adopted a frequency of 80 Hz and a voltage of 400 V_{pp}.

The choice of these specific values was informed by a study conducted by Wijekoon *et al.* (2012). The study aimed to investigate the perceived intensity of modulated friction generated by electrostatic force. The experimental results revealed significant correlations between the perception of intensity and the amplitude of the signal, with the highest sensitivity observed at a frequency of 80 Hz. Additionally, the study observed a linear correlation between the intensity of perception and the amplitude level.

In the study, voltage levels were examined using 0 dB, -6 dB, and -12 dB, which corresponded to voltages under 1.2 kV. However, it was recognized that using such high voltage levels could potentially damage the 3M plates. Therefore, based on previous study by Friaa *et al.* (2022), a fixed voltage of 200 V_{pp} was chosen instead in experiments 4.3 and 4.2.

During the experiments, the participants are instructed not to apply excessive pressure on the electrovibrating surfaces as this may impact their perception.

Participants are required to wear noise-canceling headphones due to the sound of electrovibration produced by the relay module terminals connected to the electrovibrating surfaces. These sounds indicate the activation or deactivation of electrovibration feedback, and wearing headphones helps reduce their potential influence on participants' perception and performance during the study.

During some of the experiments, to capture participants' responses regarding their perception of electrovibration feedback, a pop-up appears in the middle of the screen, asking "Did you feel any texture during the interaction?". Participants indicate their response by choosing either "Yes" or "No" on the pop-up using a mouse or keyboard. During some other experiments, there is no pop-up; however, the participants are instructed to press specific keyboard keys after finishing a trial to provide their feedback. The protocols will be discussed in detail within each experiment.

4.2 Experiment 1: electrovibrating palm rest

The goal of the accidental detection test is to see if participants experience electrovibration feedback through a palm rest while interacting with a keyboard and a mouse. The purpose of the deliberate detection test is to assess whether participants can perceive the electrovibration feedback through the electrovibrating palm rest while deliberately sliding their hands across it.

4.2.1 Test 1a: accidental detection

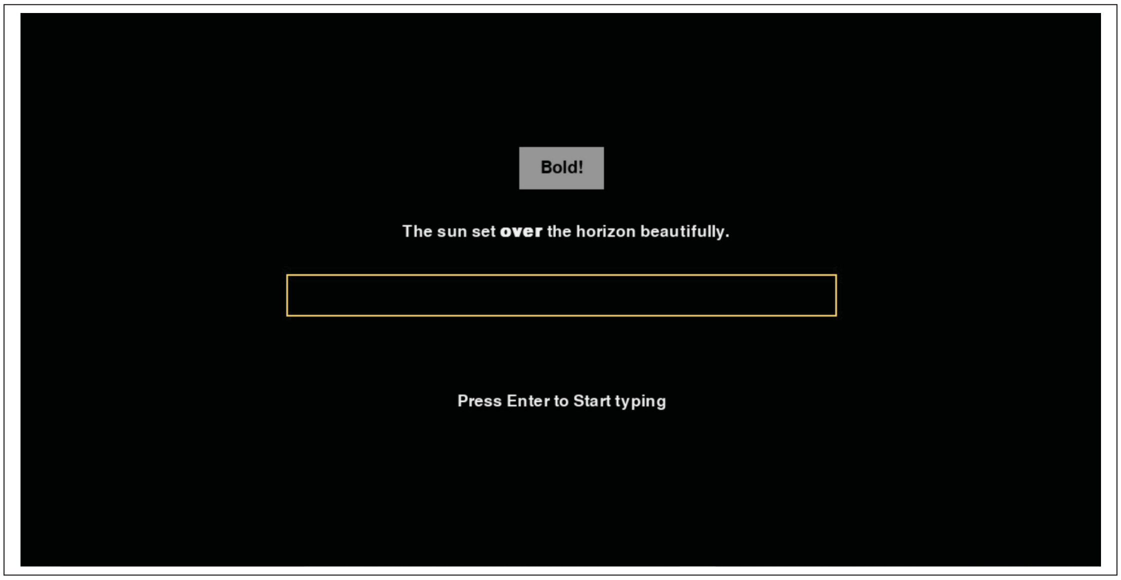
In this test, we want to look at what motion patterns allow people to notice electrovibration feedback under their palms most efficiently. Some of the motion patterns could be when participants' palms are lifted or rested on the palm rest during accidental interactions, or when typing requires the participant to press a mouse button before writing on the keyboard.

The participants are asked to type a series of letters on a keyboard while occasionally using the mouse for specific actions. In detail, we ask participants to report if they perceived electrovibration feedback while typing each of the ten sentences shown in table 4.1. The sentences are meaningful English sentences sourced from online references. Each sentence consists of 7 words, and the intention behind this choice is to ensure tasks' similar difficulty and reasonable sentence length. Furthermore, the sentences contain a consistent range of characters, with 32 to 42 characters each. As participants type the sentences, they may be required to click a button on the screen once they reach the center bolded word, which, although not always bold.

Table 4.1 Sentences used in test 1a, each consisting of 7 words

Sentences	**Number of characters**
The cat lazily stretched out her paws.	36
He played guitar for hours on end.	32
The sun set over the horizon beautifully.	40
She smiled brightly and hugged her friend.	39
The wind whispered secrets through the trees.	42
The children laughed and played in harmony.	40
He studied hard to achieve his dreams.	36
The snowflakes fell gently on the ground.	38
Autumn leaves painted the path with color.	39
The quick brown fox jumps over fences.	38

Participants are instructed to initiate each trial by pressing the Enter key (Figure 4.1). A trial comprises typing one sentence and then responding to a pop-up question. The computer interface invites the participant to type the displayed text into a text box. During the trial, participants encounter bolded words represented by a bold font, appearing randomly and equally as often as unbolded words. During that trial, a button is displayed for the participant to mouse-click when they arrive at the bolded word to make it bold and then continue typing.

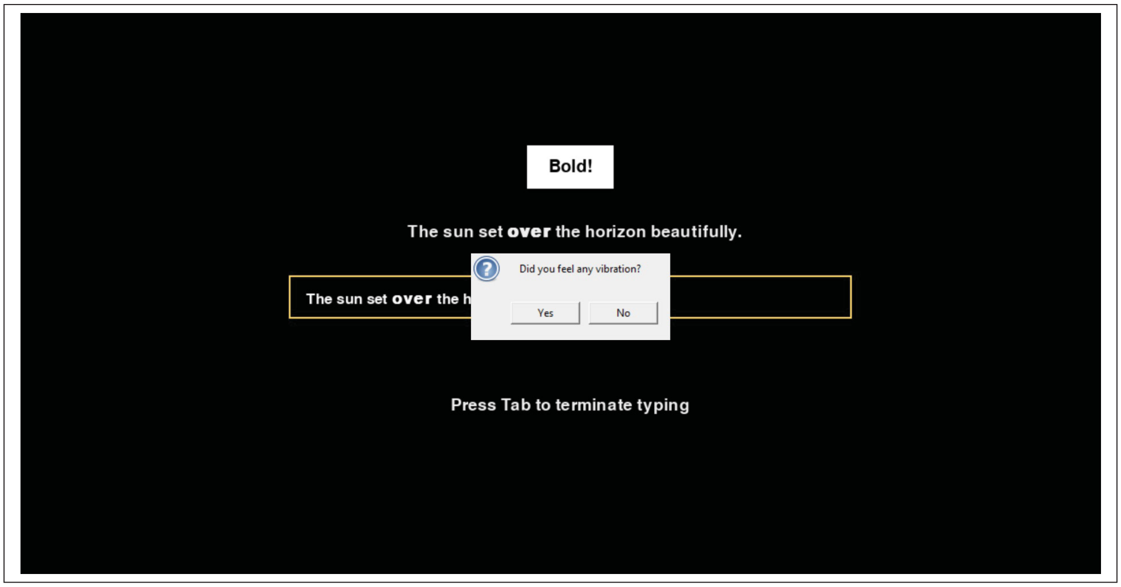


The sun set **over** the horizon beautifully.

Press Enter to Start typing

Figure 4.1 PC interface accidental detection test 1a

To end typing, the user presses the Tab key after finishing a sentence. Then, in the center of the screen, a pop-up appears inquiring if the participant felt any electrovibration. They must respond to the pop-up with the mouse button by clicking “Yes” if they perceived it and “No” if they did not perceive it (Figure 4.2). Upon answering the pop-up, a new sentence appears on the screen.



Bold!

The sun set **over** the horizon beautifully.

The sun set **over** the h

Did you feel any vibration?

Press Tab to terminate typing

Figure 4.2 Pop-up question in accidental detection test 1a

As mentioned earlier, participants are instructed to click the mouse button while typing during certain trials to test our hypothesis. Based on our early tests in Chapter 2, we anticipate that the feedback will be more noticeable when participants switch back and forth between the keyboard and the mouse while using an electrovibrating palm rest, compared to just typing movements.

During each trial, the electrovibration feedback could be either activated or not. The feedback is triggered when the participant presses the Enter key to begin the trial, but only if the specific sentence is set to activate the feedback. Once activated, the electrovibration feedback remains active until the participant presses the Tab key to signal the end of that particular session.

In this test, the activation and deactivation of electrovibration feedback are evenly distributed among sentences. This means that an equal number of sentences will have the feedback activated and an equal number of sentences will have it deactivated. Additionally, the order in which the sentences are presented is randomized, ensuring that the activation of electrovibration feedback is varied across participants. The reason behind this randomization is to prevent participants from learning a consistent pattern and potentially influencing their responses. By randomizing the order, we avoid any bias or expectancy in the participants' perception of electrovibration feedback. This approach ensures that participants cannot anticipate whether the feedback will be active or not.

Analysis

In this study, our focus is on evaluating the error rate, which measures the frequency of confusion between electrovibration feedback being on and off during the trials. We will analyze how often participants make errors in distinguishing between the two states.

Additionally, we will compare the error rates under different conditions, specifically examining the impact of mouse clicks on the participants' ability to accurately perceive electrovibration feedback. By comparing conditions with and without mouse clicks, we aim to examine whether clicking forces more movement, potentially leading to increased brushing against the surface and affecting their perception of electrovibration feedback.

Upon completion of the test, we will analyze the number of typing errors made by participants to identify those who may not have performed the task correctly. We will discard their data to ensure the validity and accuracy of the results, including data from participants who completed the tasks, with a small tolerance for number of errors, and considering whether they clicked on the bold button.

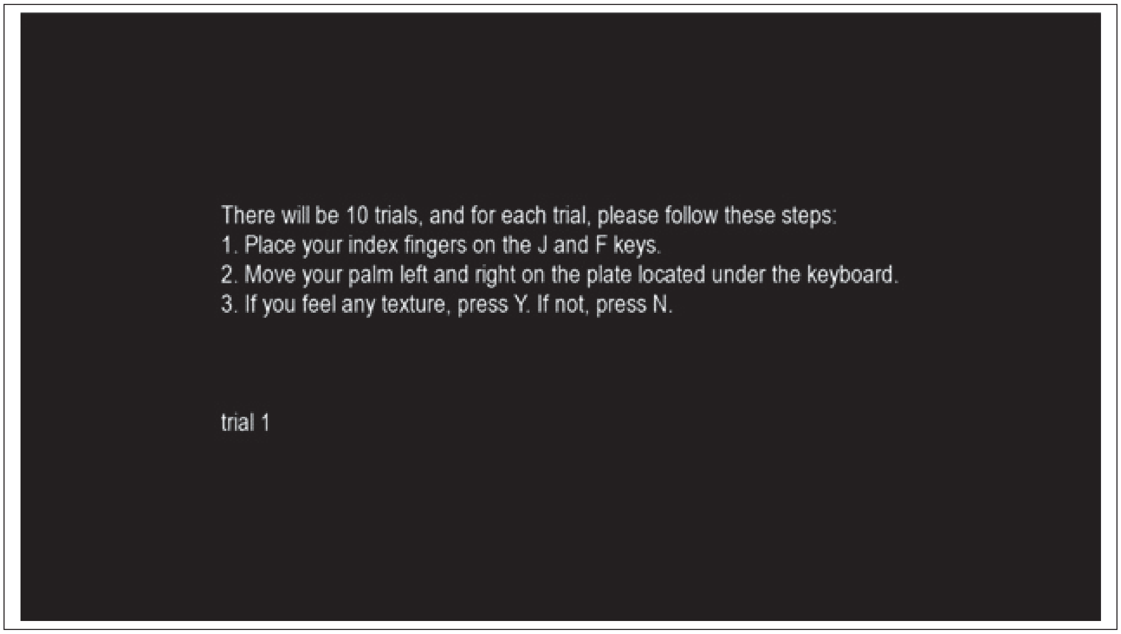
4.2.2 Test 1b: deliberate detection

The test is designed to be simple and short as we already expect from prior work that the feedback will be perceived. Therefore, it serves as a quick check to confirm participants' perception of the electrovibration feedback.

In this test, we ask participants to report if they perceive electrovibration feedback while sliding their hands on the electrovibrating palm rest. The order of activation or deactivation of electrovibration feedback is set at random for each participant in each trial. The test consists of ten trials in which the electrovibration is turned on or off in half of the trials. As explicitly stated in the PC interface instructions (Figure 4.3), participants are required to follow a specific sequence. Firstly, they need to position their index fingers on the J and F keys. Secondly, they should move their palm left and right on the electrovibrating palm rest. Finally, they are to indicate their perception results by pressing ’Y’ for yes and ’N’ for no on the keyboard.

The collected data includes the participants’ responses regarding their perception in each trial, as well as the deliberate detection time, which is the duration it takes for participants to actively explore the capacitive plate and press ’Y’ or ’N’ on the keyboard. This deliberate detection time serves as an indicator of the level of difficulty participants experience in feeling the feedback during the interaction.

The error rate is investigated in the analysis, which is calculated as the ratio of the total number of correctly detected electrovibration feedback to the total number of rendered electrovibration feedback.



There will be 10 trials, and for each trial, please follow these steps:
1. Place your index fingers on the J and F keys.
2. Move your palm left and right on the plate located under the keyboard.
3. If you feel any texture, press Y. If not, press N.

trial 1

Figure 4.3 PC interface in deliberate detection test 1b

4.3 Experiment 2: electrovibrating mouse pad

The objective of the accidental detection test is to explore the user's perception of electrovibration feedback while using an electrovibrating mouse pad during tasks on a PC interface. The objective of the deliberate detection test is to determine whether participants can consciously perceive electrovibration feedback when it is intentionally employed.

4.3.1 Test 2a: accidental detection

We aim to explore whether various factors such as the direction and distance of mouse movements, as well as the ergonomic properties of the mouse and resulting hand posture can impact the user's perception of electrovibration feedback. To test our hypothesis, we designed an experimental protocol using a pointing task commonly used in human-computer interaction (HCI). Although our experiment doesn't directly evaluate Fitts' Law, it incorporates some of its elements. Fitts' Law (Fitts, 1954) is a well-established HCI model that links movement time (MT) to the distance (A) and width (W) of the target object when using a mouse or similar pointing device. The movement time (MT) can be calculated using the equation:

$$MT = a + b \log_2 \left(\frac{2A}{W} \right)$$

a, b: *a* represents intercept and *b* represents slope in this linear regression model

A: amplitude (or distance) of movement from the source object's center to the target object's center

W: The width of the source and target objects

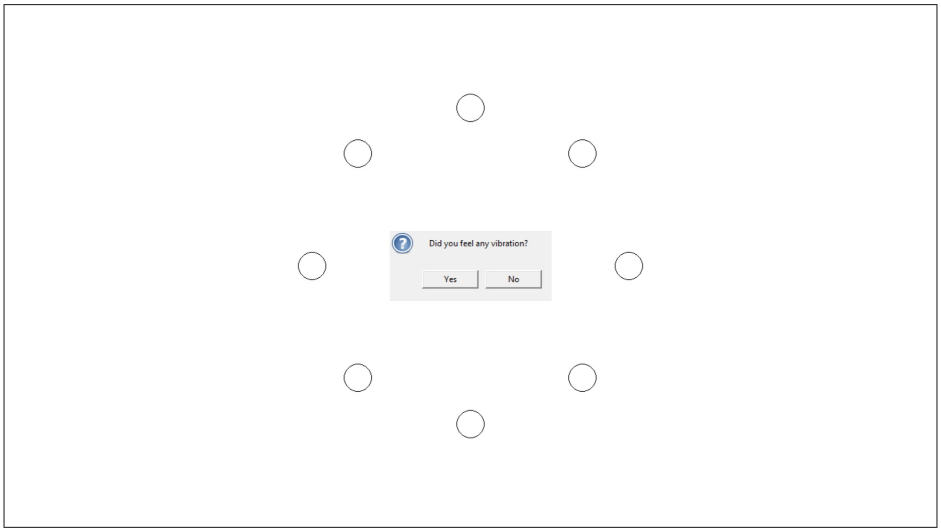
Fitts' law enables us to predict the time taken and control the distance traveled by participants to move the cursor from a source circle to a target circle in an experiment from the equation above. Fitts' Law was chosen as the basis for this test because it allows us to assess electrovibration perception in the context of a pointing task, as well as control the amount of movement, which we expect to influence electrovibration perception.

The experiment comprises several pointing trials, where the participant will be asked to start by clicking on a blue source circle and then proceed to click on a blue target circle. After each trial, a pop-up appears on the screen, asking the participant if he or she perceived any texture during that trial. The participant then moves on to the next trial by locating a new highlighted blue source circle. The above definitions are shown in Figure 4.4 and 4.5. During the test, electrovibration feedback is activated during certain trials when the participant clicks on the source circle and stops when they click on the target circle displayed on the screen.

a) source circle

b) target circle

Figure 4.4 Demonstration of source-target circles in test 2a



Did you feel any vibration?

Figure 4.5 Pop-up question in test 2a

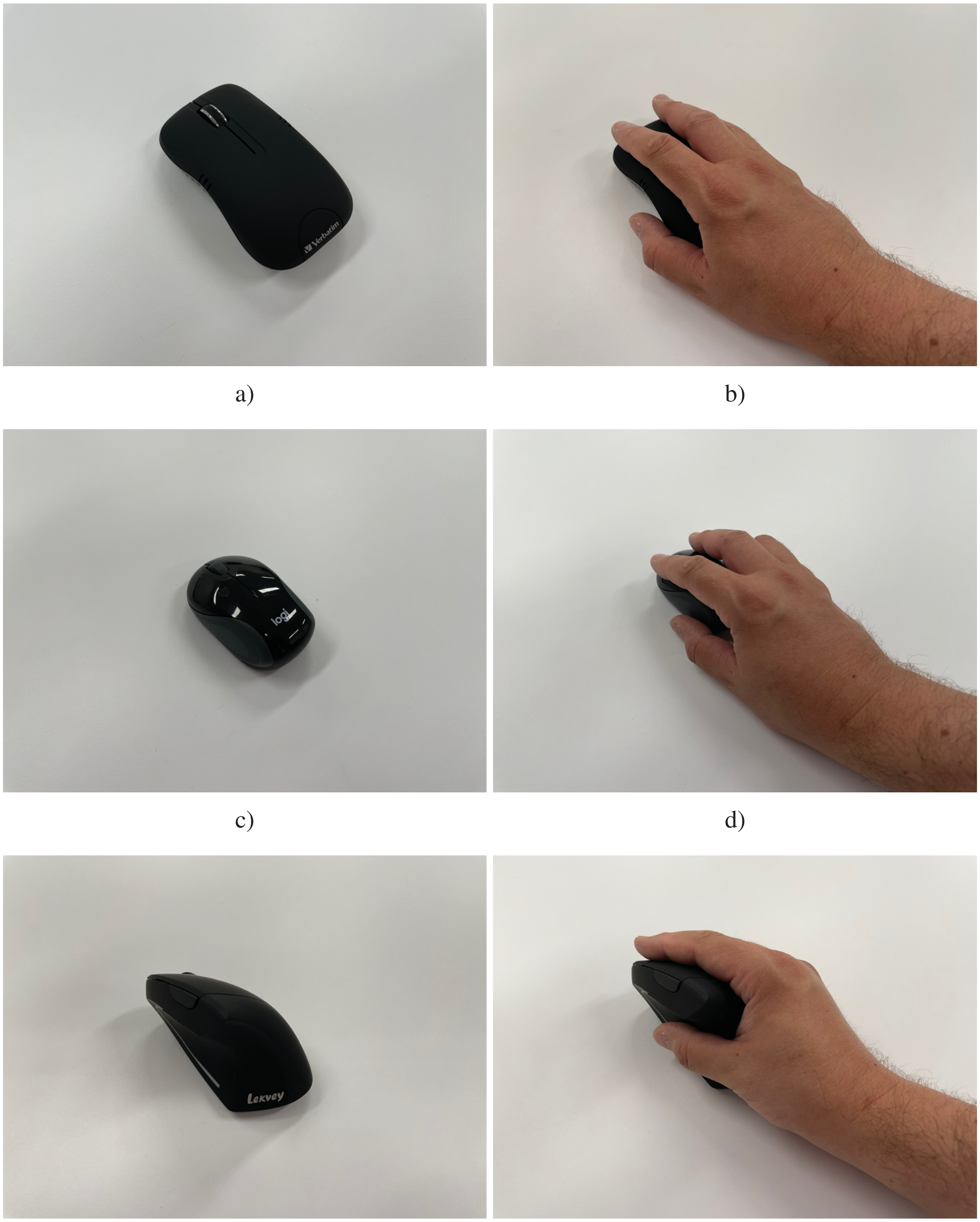
The experiment incorporates various conditions to evaluate their impact on the perception of electrovibration feedback.

1. **Mouse shape:** The effectiveness of the electrovibrating mouse pad can vary depending on the type of mouse being used and the way users hold the mouse. To better understand the impact of these factors on tactile perception, it is necessary to consider various types of mice. For this purpose, we used ergonomic computer mice, which are designed to be more comfortable to use and promote better hand posture during use.

The computer mice (Figure 4.6) we used are categorized into three types: regular mouse, mini mouse, and ergonomic vertical mouse. The regular mouse is the most commonly used type and is held with a pronated wrist, which can cause strain on the hand and wrist. The mini mouse's compact size enables a grip with a few fingers, and its ergonomic design allows more of the hand to rest on the mouse pad. The ergonomic vertical mouse is held in a neutral grip, which reduces the strain on the wrist and promotes a more natural posture.

The way participants hold their computer mouse, especially when using ergonomic mice, can impact their perception. This is because different grip styles, hand sizes, and mouse designs can affect the extent of contact between the hand and the electrovibrating mouse pad. For example, some participants may have a more relaxed grip with greater palm contact, while others may use a fingertip grip with less palm contact. Smaller mice tend to increase the contact area between the mouse and the mouse pad, as they allow more of the hand's surface area to come into contact with the mouse. Consequently, participants may rest more of their palm and fingers on the mouse pad, resulting in increased contact compared to larger mice. Conversely, ergonomic mice, with their broader base, enable increased palm contact with the mouse pad.

It's important to recognize that the sensitivity of these mice, measured in DPI (dots per linear inch), varies, leading to differences in cursor speed. DPI signifies the number of dots (or pixels) the mouse cursor travels on the screen per inch of physical movement. Higher DPI settings result in more pixels covered with the same physical movement, thus producing faster on-screen mouse movements. Conversely, lower DPI settings yield slower movements. The regular mouse operates at 1200 DPI, the mini mouse at 1000 DPI, and the ergonomic vertical mouse's DPI is adjustable to 800/1200/1600. This divergence leads to varying speeds when dragging mice across the pad. As DPI values are hardware-specific and unadjustable, compensating can be achieved by modifying windows pointer speed. This ensures that for each inch of mouse motion, the cursor moves 2.5 to 3 inches on-screen. Calibrating considers each mouse's DPI while deactivating mouse acceleration settings to standardize distances traveled on the electrovibrating mouse pad, maintaining consistency across all mice.



a) b)

c) d)

e) f)

Figure 4.6 (a) and (b) depict regular computer mouse, (c) and (d) show mini mouse, and (e) and (f) display ergonomic vertical mouse

2. **Movement amplitude:** Movement amplitudes represent the distances from the center of the source circle to the center of the target circle. Longer mouse movements increase the contact duration and, consequently, the likelihood of feeling the electrovibration effect. The choice of the longer distance for mouse movement takes into consideration the dimensions of the monitors to ensure that target circles remain visible on the screen. Specifically, the longest distance that the mouse cursor travels between two source and target circles is approximately equal to the height of the screen. As an example, taking into account that the height of the experimental monitor measures 6.9 `in`, the greatest distance from the screen's center to the center of the circles amounts to 3.2 `in`. Two additional distances are also involved: the shortest distance spans 1 `in`, while the intermediate distance spans 1.9 `in`.

It's important to note that the radius of all circles remains uniform and consistent throughout the course of the experiment. We have made the decision to opt for a radius of 0.12 `in`.

3. **Movement angle:** The experiment takes into account the direction of movement from source to target, incorporating horizontal, vertical, and diagonal directions to encompass various hand movement patterns. This approach ensures that the study accounts for potential confounding effects that may arise from conducting a unidirectional experiment. The experiment encompasses a total of eight different directions of mouse dragging. An illustration is presented in Figure 4.7.

To examine and compare the effects of electrovibration feedback when it is activated and deactivated, each movement angle is repeated twice: once with electrovibration and once without electrovibration.

We have organized the above conditions in a nested manner, with Condition 1 encompassing Condition 2, and Condition 2 further containing Condition 3. We are investigating three ergonomic computer mice, and each of these mice is subjected to a series of trials involving three distinct movement amplitudes. Moreover, each movement amplitude is tested at eight different movement angles. To ensure reliability, the mouse is dragged in each direction twice. Therefore, each movement amplitude consists of 16 trials. The order in which these trials are presented is randomized.

The total number of trials per participant is determined by combining the variations in mice (3), movement amplitudes (3), directions (8), and trial repetitions (2). This yields a total of 144 trials per participant.

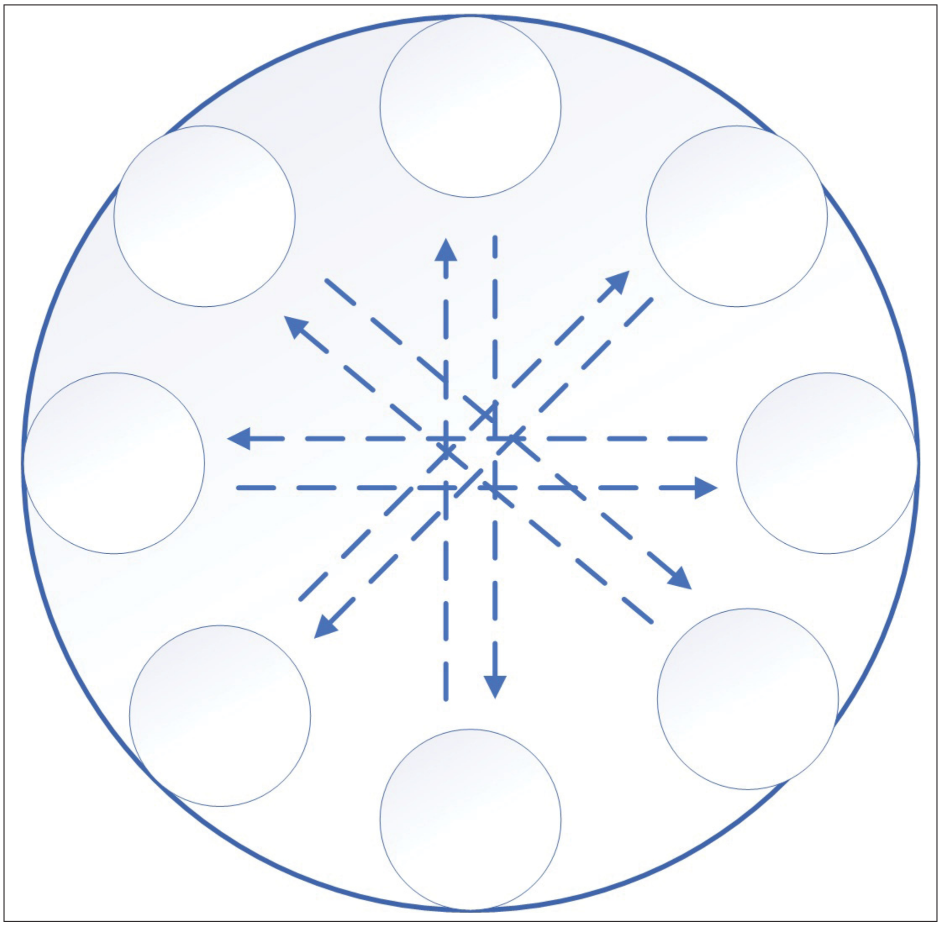


Figure 4.7 Directions illustration in test 2a

Analysis

In this experiment, we will analyze several key outputs by recording the following metrics for each trial:

a) Participants' responses to the pop-up.

b) By using the measured values from time taken and the distance covered, we validate whether we successfully influenced amplitude as intended.

In the analysis of this test, we want to see the effect of movement speed which is a combination of distance and target size. The movement time and distance traveled data collected from the experiment will be used in several ways to confirm the intended variations in speed and distance and to ensure consistency between participants.

4.3.2 Test 2b: deliberate detection

In this test, participants are not provided with any specific interface to interact with. Instead, they are instructed to naturally hold each of the three mice and drag them on the electrovibrating mouse pad. If they feel any tactile sensations or texture on their palm or hand, they should press the “Y” key on the keyboard. Otherwise, they should press the “N” key. All three mice are used in this test.

In this test, there are a total of 10 trials. The activation and deactivation of electrovibration are evenly distributed among these trials to ensure equal representation. This means that an equal number of trials involve electrovibration activation and deactivation. Furthermore, the order in which these 10 trials are presented to each participant are randomized.

4.4 Experiment 3: electrovibrating keyboard keys

The purpose of this experiment is to investigate how participants perceive electrovibration feedback when using electrovibrating keyboard keys during tasks on a PC interface.

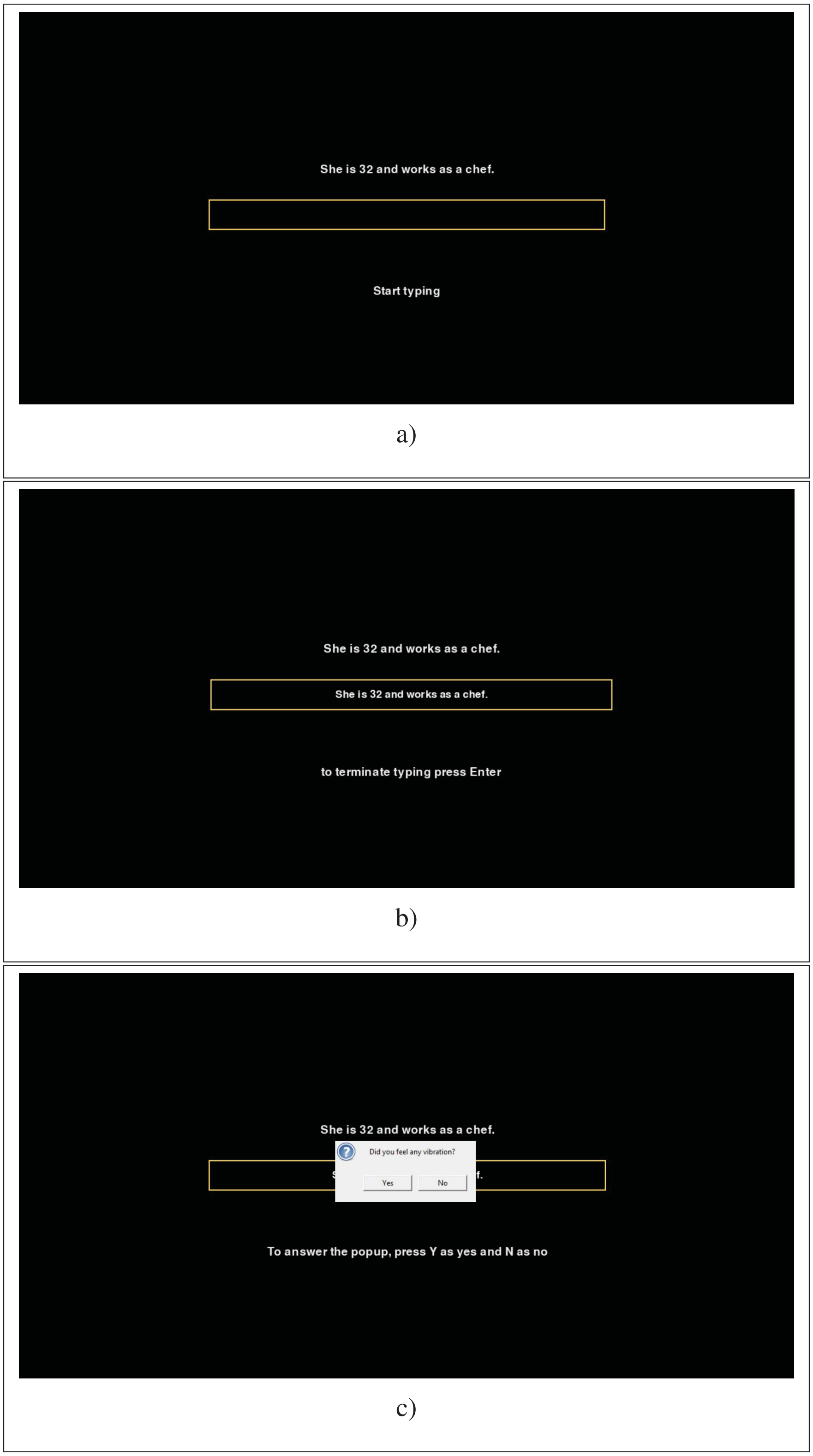
4.4.1 Test 3a: accidental detection

We aim to examine the potential influence of factors such as typing speed and the use of one or multiple fingers to explore the keys on the perception of electrovibration feedback.

In this test, we have developed a PC interface that allows participants to interact with the nine key of the numeric keypads. This interface presents participants with a typing test comprising different trials. Participants will encounter a total of 16 sentences, with each sentence serving as a trial. These sentences, sourced from online references, are meaningful English sentences and vary in length. Each sentence contains a distinct combination of two sequential numbers (e.g., 32, 45), and the number combinations within each sentence are completely random. Random two-digit combinations in each sentence ensures that participants encounter various numerical sequences during the typing test.

To maintain control over the typing process, participants will always start from the left side of the keyboard and then slide to the numeric keypad. This control ensures a consistent starting point for all participants.

Participants will conduct the experiment without using a mouse, relying solely on the keyboard for input. To begin the test, they will be instructed to type the displayed sentence into the provided text box. Upon completing the full sentence, participants will end the trial by pressing the Enter key, following the interface's instructions. Afterward, a pop-up will appear, asking participants if they perceived any sensation. They will use the "Y" key for "yes" and the "N" key for "no" on the keyboard to respond to the pop-up (Figure 4.8). As soon as they answer the pop-up, a new sentence will appear on the screen to continue the process.



She is 32 and works as a chef.

Start typing

a)

She is 32 and works as a chef.

She is 32 and works as a chef.

to terminate typing press Enter

b)

She is 32 and works as a chef.

Did you feel any vibration?

To answer the popup, press Y as yes and N as no

c)

Figure 4.8 An illustration of a trial in accidental detection test 3a

In this experiment, there are a total of 16 sentences. The activation and deactivation of electrovibration feedback are evenly and randomly distributed among the sentences. Specifically, half of the sentences are randomly selected to activate the electrovibration feedback, while the other half is set to deactivate it. Additionally, the order in which these sentences are presented to each participant is also randomized.

Upon displaying the sentence, the electrovibration feedback will be rendered on the electrovibrating keyboard keys corresponding to the two numbers present at once in that sentence. The electrovibrating keyboard keys continue to provide feedback until the participant presses the enter key on the keyboard, indicating the termination of the typing session.

Analysis

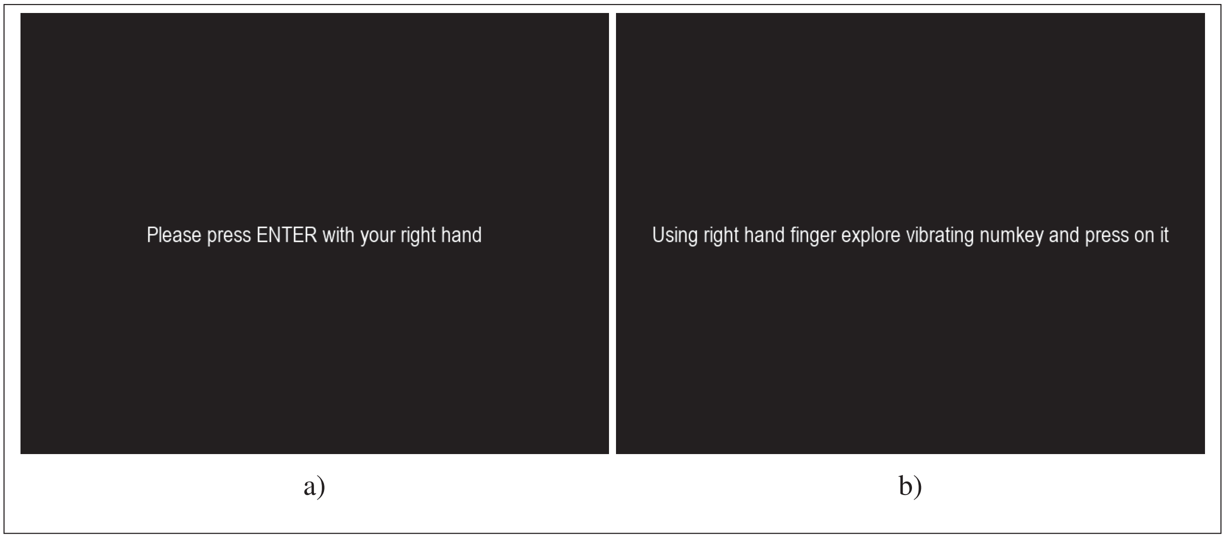
We want to evaluate if the presence of feedback impacts their typing speed and whether they perceived the feedback.

4.4.2 Test 3b: deliberate detection

In this test, participants are asked to identify the key that they feel has electrovibration. They are provided with an interface displaying instructions (Figure 4.9), which they need to follow. To begin the task, participants press the Enter key on the keyboard using their right-hand fingers throughout the test. After that, they are instructed to explore the numeric keypad and locate the key they feel electrovibrating on their skin.

In this test, participants are free to use either one or multiple fingers to scan the numeric keypad. The test always starts from the Enter key as the initiating point to simulate the participants' movement from left to right, as if they are typing on the keyboard and need to press a key on the numeric keypad.

There are a total of 18 trials. Each trial corresponds to one of nine keys on the numeric keypad, and all nine keys are presented twice during the course of the test. The order in which the keys



Please press ENTER with your right hand

a)

Using right hand finger explore vibrating numkey and press on it

b)

Figure 4.9 An example depicting a trial in the deliberate detection 3b test

are presented to the participants is randomized to avoid any potential bias. Throughout the test, the electrovibration feedback is activated for the presented key.

Analysis

We are analyzing whether participants were able to locate the electrovibrating key and also how long it takes for them to find and press the key from the previous trial.

4.5 Limitations

To ensure control over the experiment, certain conditions were chosen, focusing on one level of frequency, voltage, and shapewave. However, these settings may not be optimal, especially since electrovibration feedback on the hand has not been extensively studied.

Additionally, the experiment did not account for the impact of contact force applied by the participants' hands on the electrovibrating surfaces. Although participants were instructed to primarily rest their palm without applying excessive pressure, this factor could still influence perception.

Another limitation is the design of the electrovibrating mouse pad, which is optimized for right-handed participants. This could potentially affect the performance and perception of left-handed participants during tasks requiring mouse interaction.

CONCLUSION AND RECOMMENDATIONS

In recent times, haptic feedback, which provides touch sensations to enhance user experiences, has gained importance. Technologies like electrovibration simulate textures and vibrations by adjusting friction between surfaces and fingertips. This has transformed interactions with digital environments. Our project aimed to integrate electrovibration into desktop computers.

This research built upon earlier work in electrovibration, particularly focusing on its perception on the palm and fingertip. Our goals were to explore electrovibration's design space in PC peripherals and study how users perceive its feedback.

The thesis structure covered haptic technology, electrovibration, and its integration into PC peripherals. It details brainstorming, prototype design, and user experiment plans for each surface area.

We started by brainstorming design options for PC peripherals. This led us to focus on three surfaces: palm rest, mouse pad, and keyboard keys. These surfaces were chosen to provide tactile experiences. We generated ideas, created haptic sketches, and designed prototypes for each surface. Our prototypes combined hardware and software components. We developed a signal generating system for electrovibration and unique hardware for each surface. Corresponding software was designed to control and activate electrovibration.

The next step was planning user experiments. We wanted to see if participants could perceive electrovibration feedback accidentally (while typing or using a mouse) and deliberately (by touching the surfaces). To accomplish this, we developed six distinct experiments, each tailored to the specific electrovibrating surface, encompassing varied experimental protocols. The described experiments investigate how electrovibration feedback affects user interaction with PC peripherals, examining its perception during mouse pad usage, mouse movement, and keyboard typing. These experiments encompass accidental and deliberate detection tests, exploring factors like movement distance, direction, typing speed, and finger usage.

Our achievements include identifying promising areas for electrovibration integration, developing functional prototypes, and planning comprehensive experiments. This work lays the foundation for enhancing user experiences in PC peripherals through electrovibration, offering three prototypes as examples.

In our future research, we intend to recruit participants, conduct the experiments designed in this study, and subsequently analyze and share the findings. We expect the participants will be able to detect electrovibration feedback across all three electrovibrating surfaces through deliberate interactions, as well as in scenarios of accidental interactions. These could include situations when there is increased contact with the electrovibrating surface, for example, when there is significant mouse movement over an electrovibrating mouse pad or when the user has to move back and forth between the keyboard and the mouse while using an electrovibrating palm rest

Future research should address limitations related to fixed settings, such as a fixed level of frequency, voltage, and waveform. Furthermore, it should address design biases, such as its applicability only to right-handed participants, with the aim of optimizing the feedback experience and accommodating diverse user requirements. While the study focused solely on constant electrovibration patterns due to simplicity and time constraints, there's potential for further investigation into unexplored patterns like pulsating signals, offering prospects for future exploration.

APPENDIX I

RESULT OF IDEATION SESSIONS

- **Input devices:**
  - **Input ports:** Electrovibration can create a tactile sensation when a user plugs in a USB cable into a port, confirming that the connection has been made.
  - **Mouse pad:** Electrovibration can be used to provide a tactile sensation when mouse is dragged from point A to point B on MousePad.
  - **Joystick mice:** Electrovibration can create a sensation of resistance or feedback when a user moves the joystick in different directions, making it feel more responsive and realistic in gaming scenarios. we could think of embedding the electrovibration technology with the top surface of the joystick's grip, side surfaces or buttons or triggers.
  - **Game controller:** Electrovibration can create different levels of vibration or feedback in response to various in-game events or actions, such as a weapon recoil or a character's movement. This can enhance the player's immersion and provide more accurate feedback for their actions.
  - **Keyboard keys:** Electrovibration can provide different types of tactile feedback for different keys, such as a softer vibration for function keys and a more noticeable vibration for letters and numbers. This can help users to type more quickly and accurately, especially in noisy or low-light environments where it may be difficult to see the keys clearly.
  - **Trackpad or Touchpad:** Electrovibration can be used to provide haptic feedback during scrolling or clicking on the trackpad. This can help users to more accurately control the cursor and avoid unintentional clicks or movements.
  - **Resting area of the keyboard:** Electrovibration can be used to provide a subtle feedback when the user rests their hand on the keyboard and move their palms accidentally or purposefully.The vibrations can be customized based on the user's typing habits or preferences, such as a softer vibration for light typists and a stronger vibration for heavy typists.

  - **Scroll wheel**: Electrovibration can be used to provide tactile feedback when scrolling on a mouse's scroll wheel. This feedback can indicate how fast or slow the user is scrolling, or provide a different sensation when scrolling through different types of content (e.g. a rougher vibration for scrolling through a webpage with many images vs. a smoother vibration for scrolling through a document with mostly text).
  - **Touchscreen:** Electrovibration can be used to provide haptic feedback on a touchscreen device, such as a tablet or smartphone. This feedback can provide a tactile sensation when the user taps or swipes on the screen, giving the impression of physical buttons or textures on a flat surface. Additionally, electrovibration can provide feedback when interacting with different types of content, such as a different sensation when scrolling through a list vs. selecting a button.
- **Office supplies:**
  - **Papers:** When flipping through pages on a digital device, electrovibration can be used to simulate the feeling of flipping through physical pages. As the user swipes their finger across the screen, the device can vibrate in response to the friction between their finger and the screen, creating a sensation that feels like turning pages.
  - **Stapler:** When using a stapler, electrovibration can be used to provide a tactile sensation that confirms the paper has been properly stapled. As the user presses down on the stapler, the device can vibrate to create a sense of feedback that confirms the paper has been stapled correctly.
  - **Pen holder:** When placing or removing a pen from a holder, electrovibration can be used to create a tactile sensation that confirms the pen is securely in place. As the user slides the pen into the holder, the device can vibrate to create a sense of feedback that confirms the pen is in the proper position.
  - **Pen/cil:** When writing or drawing, electrovibration can be used to provide a tactile sensation that gives the user a sense of precision and feedback. As the user moves the pen or pencil across the surface, the device can vibrate in response to the friction between the writing implement and the surface, creating a sensation that feels like the pen or pencil

is “grabbing” the surface and providing a sense of feedback that can help the user make more precise strokes.

- **Environment:**
  - **Under the desk:**Electrovibration can be used to create a tactile sensation when the user’s foot hits a specific area under the desk, such as a footrest or cable management area. As the user’s foot makes contact with the surface, the device can vibrate to create a sense of feedback that confirms the user has made contact with the intended area.
  - **Side of the desk:** Electrovibration can be used to provide a tactile sensation when the user touches a specific area on the side of the desk, such as a button or control panel. As the user’s finger makes contact with the surface, the device can vibrate to create a sense of feedback that confirms the user has touched the intended area.
  - **Chair legs/base with wheels:** Electrovibration can be used to provide haptic feedback when the chair is moving on a carpeted or hardwood floor. As the chair moves, the device can vibrate to create a sense of feedback that confirms the chair is moving smoothly and to provide a sense of motion to the user.
  - **Chair seat/backrest** Electrovibration can be used to provide a tactile sensation when the user is sitting in the chair, giving the user a sense of comfort and support. As the user settles into the chair, the device can vibrate to create a sense of feedback that confirms the user is seated comfortably and to provide a sense of support to the user’s back.
  - **Floor:** Electrovibration can be used to create a tactile sensation on the floor, providing feedback during activities such as exercise or gaming. As the user moves on the floor, the device can vibrate to create a sense of feedback that confirms the user is moving smoothly and to provide a sense of motion or impact during activities such as jumping or running.
  - **Phone (landline), cup/mug, Armrest, Wall, lamp**
- **Other Peripherals:**
  - **Speaker:** Electrovibration can be used in a portable Bluetooth speaker to provide a tactile sensation that enhances the bass response, making the sound feel more immersive and powerful.

- **Headphones:** Electrovibration can be used to provide haptic feedback during audio playback, enhancing the overall audio experience.
- **Webcam:** Electrovibration can be used in a high-end webcam to create a tactile sensation when the user is adjusting the zoom or focus, allowing for precise adjustments without having to rely solely on visual cues.
- **Printer:** Electrovibration can be used to create a tactile sensation when printing, giving the user a sense of confirmation that the document has been printed.
- **Monitor stand:** Electrovibration can be used to provide a tactile sensation when adjusting the height or angle of the monitor, providing feedback and precision.
- **Desktop computer case:** Electrovibration can be used to create a tactile sensation when adjusting or installing
- **Scanner, Microphone, 3D printer, Lid of closed laptop, Monitor frame, headphones**

In addition, we also brainstormed possible real-world applications of electrovibration technology and came up with several ideas.

- **Feedback for sliding on keys as input:** Electrostatic vibration could provide tactile feedback when sliding on keys, enhancing the user's experience and making typing more efficient.
- **Highlight keys on the keyboard:** Electrostatic vibration could also highlight specific keys on the keyboard, making it easier for users to find certain letters, numbers, or symbols.
- **Battery status on power button:** Electrostatic vibration could indicate the battery status of a device when the power button is pressed, without the need for a separate battery level indicator.
- **Action permitted or not:** Electrostatic vibration could provide feedback to users when certain actions are permitted or not, such as when trying to access a restricted app or file.
- **Replicate features of virtual keyboards:** Electrostatic vibration could replicate the features of virtual keyboards, such as the ability to feel the buttons as you type.
- **Meeting reminder:** Electrostatic vibration could remind users of upcoming meetings or appointments by providing a tactile notification.

- **Texture rendering:** Electrostatic vibration could simulate textures and provide users with a more immersive experience in virtual reality or gaming environments.
- **If someone is typing:** Electrostatic vibration could indicate when someone is typing on a nearby keyboard or device, allowing for better communication and collaboration in shared spaces.
- **Assisting in learning how to type:** Electrostatic vibration could assist users in learning how to type by providing tactile feedback when they make mistakes or hit the wrong keys.
- **Notification system for PC/phone notification:** Electrostatic vibration could provide a tactile notification for incoming messages or notifications on a PC or mobile device, without the need for visual or auditory cues.
- **Log-in authentication:** Electrostatic vibration could provide a unique tactile pattern for log-in authentication, adding an extra layer of security to devices and systems.
- **Feeling fabric:** Electrostatic vibration could simulate the feeling of different fabrics on a touch screen, enhancing the user's experience when shopping for clothes online.
- **Is this on? (mic, camera):** Electrostatic vibration could indicate whether the microphone or camera is on or off, providing an added layer of privacy and security for users.
- **Affect:** Electrostatic vibration could provide feedback on the emotional affect of text messages or other digital content, enhancing the user's emotional experience and potentially reducing negative emotions.
- **Ambient feedback:** Electrostatic vibration could provide ambient feedback on the overall state of a system or device, indicating whether it is running smoothly or encountering problems.
- **Upcoming meeting:** Electrostatic vibration could remind users of upcoming meetings or appointments by providing a tactile notification.
- **Time keeping:** Electrostatic vibration could provide feedback on the passing of time, enhancing the user's awareness of the passage of time.
- **Emotion Regulation:** Electrostatic vibration could help users regulate their emotions by providing feedback on their emotional state or offering calming vibrations.

- **Digital well-being:** Electrostatic vibration could promote digital well-being by reminding users to take breaks, providing feedback on screen time, or promoting healthy habits.
- **System status:** Electrostatic vibration could indicate the status of a system or device, such as whether it is connected to a network, running low on memory, or experiencing other issues.
- **Activity:** Electrostatic vibration could provide feedback on the level of activity or usage of a device, indicating whether it is being used frequently or not.

BIBLIOGRAPHY

Akamatsu, M. (1994). Touch with a mouse-a mouse type interface device with tactile and force display. *Proceedings of 1994 3rd IEEE International Workshop on Robot and Human Communication*, pp. 140–144.

Asai, K. et al. (2015). Revisiting gradient-based haptic rendering for lateral force feedback in SPIDAR-mouse. *2015 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE)*, pp. 1–6.

Basdogan, C. et al. (2020). A review of surface haptics: Enabling tactile effects on touch surfaces. *IEEE transactions on haptics*, 13(3), 450–470.

Bau, O. et al. (2010). TeslaTouch: electrovibration for touch surfaces. *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, pp. 283–292.

Bau, O. et al. (2012). REVEL: tactile feedback technology for augmented reality. *ACM Transactions on Graphics (TOG)*, 31(4), 1–11.

Choi, H. et al. (2003). Design of novel haptic mouse and its applications. *Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003)(Cat. No. 03CH37453)*, 3, 2260–2265.

Culbertson, H. et al. (2018). Haptics: The present and future of artificial touch sensation. *Annual Review of Control, Robotics, and Autonomous Systems*, 1(1), 385–409.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology*, 47(6), 381.

Friaa, B. et al. (2022). A Conceptual and Experimental Exploration of Electrovibration on the Palm and the Body. *2022 IEEE Haptics Symposium (HAPTICS)*, pp. 1–6.

Goldstein, E. (2013). Sensation and perception 8th edition.(eds Hague, JD et al.) Ch. 14, 343–348. Wadsworth.

Hatzfeld, C. et al. (2016). *Engineering haptic devices*. Springer.

Hayward, V. et al. (2004). Haptic interfaces and devices. *Sensor review*, 24(1), 16–29.

Hayward, V. et al. (2007). Do it yourself haptics: part I. *IEEE Robotics & Automation Magazine*, 14(4), 88–104.

Holliins, M. et al. (1993). Perceptual dimensions of tactile surface texture: A multidimensional scaling analysis. *Perception & psychophysics*, 54, 697–705.

Hollins, M. et al. (2000). Individual differences in perceptual space for tactile textures: Evidence from multidimensional scaling. *Perception & Psychophysics*, 62, 1534–1544.

Israr, A. et al. (2012). Tactile feedback on flat surfaces for the visually impaired. In *CHI'12 Extended Abstracts on Human Factors in Computing Systems* (pp. 1571–1576).

Jones, L. (2018). *Haptics*. MIT press.

Kaczmarek, K. A. et al. (2006). Polarity effect in electrovibration for tactile display. *IEEE Transactions on Biomedical Engineering*, 53(10), 2047–2054.

Karunanayaka, K. et al. (2013). Haptic mouse, enabling near surface haptics in pointing interfaces. *Proc. ACHI*.

Kuchenbecker, K. J. (2018). Haptics and haptic interfaces. In *Encyclopedia of robotics*. Springer.

Lederman, S. J. (1981). The perception of surface roughness by active and passive touch. *Bulletin of the Psychonomic Society*, 18(5), 253–255.

Lederman, S. J. et al. (1972). Fingertip force, surface geometry, and the perception of roughness by active touch. *Perception & psychophysics*, 12, 401–408.

Lederman, S. J. et al. (2009). Haptic perception: A tutorial. *Attention, Perception, & Psychophysics*, 71(7), 1439–1459.

Lim, J. et al. (2019). Touchphoto: Enabling independent picture taking and understanding for visually-impaired users. *2019 International Conference on Multimodal Interaction*, pp. 124–134.

Loomis, J. M. et al. (1986). Tactual perception. *Handbook of perception and human performances*, 2(2), 2.

Lu, L. et al. (2019). A surface texture display for flexible virtual objects. *Haptic Interaction: Perception, Devices and Algorithms 3*, pp. 129–133.

Mallinckrodt, E. et al. (1953). Perception by the skin of electrically induced vibrations. *Science*, 118(3062), 277–278.

McGlone, F. et al. (2010). The cutaneous sensory system. *Neuroscience & Biobehavioral Reviews*, 34(2), 148–159.

Oey, H. et al. (2004). Vibration thresholds and equal vibration levels at the human fingertip and palm. *5th International Congress on Acoustics*, pp. 1–4.

Okamoto, S. et al. (2012). Psychophysical dimensions of tactile perception of textures. *IEEE Transactions on Haptics*, 6(1), 81–93.

Osgouei, R. H. et al. (2019). Data-driven texture modeling and rendering on electrovibration display. *IEEE Transactions on Haptics*, 13(2), 298–311.

Ozioko, O. et al. (2022). Smart tactile gloves for haptic interaction, communication, and rehabilitation. *Advanced Intelligent Systems*, 4(2), 2100091.

Park, W. et al. (2011). Haptic mouse interface actuated by an electromagnet. *2011 International Conference on Complex, Intelligent, and Software Intensive Systems*, pp. 643–646.

Ryu, S. et al. (2018). Mechanical vibration influences the perception of electrovibration. *Scientific reports*, 8(1), 4555.

Savioz, G. et al. (2009). Towards self-sensed drives in linear haptic systems. *2009 International Conference on Electrical Machines and Systems*, pp. 1–5.

Savioz, G. et al. (2011). Miniature short-stroke linear actuator. *IEEE Industry Applications Magazine*, 17(6), 14–19.

Shultz, C. D. et al. (2015). Surface haptics via electroadhesion: Expanding electrovibration with Johnsen and Rahbek. *2015 ieee world haptics conference (whc)*, pp. 57–62.

Smith, A. M. et al. (2002). Role of friction and tangential force variation in the subjective scaling of tactile roughness. *Experimental brain research*, 144, 211–223.

Strese, M. et al. (2018). A tactile computer mouse for the display of surface material properties. *IEEE Transactions on Haptics*, 12(1), 18–33.

Tang, H. et al. (1998). A microfabricated electrostatic haptic display for persons with visual impairments. *IEEE Transactions on rehabilitation engineering*, 6(3), 241–248.

Taylor, M. et al. (1975). Tactile roughness of grooved surfaces: A model and the effect of friction. *Perception & Psychophysics*, 17, 23–36.

Vardar, Y. (2020). *Tactile perception by electrovibration*. Springer.

Vardar, Y. et al. (2020). Effect of Waveform on Tactile Perception by Electrovibration. *Tactile Perception by Electrovibration*, 43–68.

Wijekoon, D. et al. (2012). Electrostatic modulated friction as tactile feedback: Intensity perception. *Haptics: Perception, Devices, Mobility, and Communication: International Conference, EuroHaptics 2012, Tampere, Finland, June 13-15, 2012. Proceedings, Part I*, pp. 613–624.