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**FACULTY OF GRADUATE AND  
POSTDOCTORAL STUDIES**

**Lara A. Rahal**

AUTEUR DE LA THÈSE / AUTHOR OF THESIS

**M.A.Sc. (Electrical and Computer Engineering)**

GRADE / DÉGRÉE

**School of Information Technology and Engineering**

FACULTÉ, ÉCOLE, DÉPARTEMENT / FACULTY, SCHOOL, DEPARTMENT

**Continuous Tactile Perception Algorithms for Vibrotactile Displays**

TITRE DE LA THÈSE / TITLE OF THESIS

**A. El Saddikl**

DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

**EXAMINATEURS (EXAMINATRICES) DE LA THÈSE / THESIS EXAMINERS**

**M. Frizel**

**S. Sihrmohammadil**

**Gary W. Slater**

Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

# Continuous Tactile Perception Algorithms for Vibrotactile Displays

by

Lara A. Rahal

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Faculty of Graduate and Postdoctoral Studies  
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# Abstract

Today, the digital community has strongly allied with rich sensory human computer interfaces (HCIs) to better understand how people interact via their sense of touch. A variety of touch interaction systems are essential for real environments, such as teleconferencing systems for remote interpersonal communications, and virtual environments, such as interacting with virtual scenes using personal computers for gaming applications. Through our sense of touch, we are capable of perceiving different types of stimuli such as pressure, vibration, pain, temperature and position. Psychologists, physiologists, and engineers have collaborated to study touch and advance the understanding of the human senses.

In this research at the University of Ottawa, we leverage knowledge of the psychology and perception of haptics to better understand the human tactile sensory system. We utilize a human sensory illusion called the “funnelling illusion” to display a dynamic tactile sensation, such as a smooth, continuous sensation on the human skin, with low-resolution vibrotactile actuators. After obtaining the illusion of a continuous movement of one tactile stimulus, we investigate the influence of temporal intensity changes of adjacent vibrotactile actuators located on the dorsal of the human forearm and upper arm. Furthermore, we examine the quality of the continuous movement according to the intensity change of the vibrotactile actuators in a linear and logarithmic pattern. Initial psychophysical experiments have revealed correlations between the distance, orientation and temporal order of the vibrotactile actuators with the preferred intensity variation, substantiating our research direction.

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## Acronyms

**HCI:** Human Computer Interface.

**DOS:** Duration Of the Stimulus.

**ISOI:** Interstimulus Onset Interval.

**SOA:** Stimulus Onset Asynchrony.

**VCT:** Voice Coil Tactor.

**DCT:** Direct Current Tactor.

**msec:** Millisecond.

**mm:** Millimeter.

**PS:** Phantom Sensation.

**AM:** Apparent Movement.

**SMA:** Shape Memory Alloy.

**PWM:** Pulse Width Modulation.

**MCU:** Microcontroller Unit.

**AC:** Alternating Current.

**V:** Voltage.

**ANOVA:** Analysis Of Variance.

**SPSS:** Statistical Package for the Social Sciences.

# Chapter 1

## Introduction

### 1.1 Background

Haptics is a term derived from the Greek verb, “haptesthai,” meaning “to touch,” and refers to the study of tactile and kinesthetic feedback with the physical interaction in the external real or virtual environment. Kinesthetic information is the information human senses with their motor receptors such as, force and motion and tactile information is the information human senses with their skin receptors such as feeling the texture of an object.[31]

Touch plays a major, everyday role in human development and social interactions, and is recognized as the most reliable sense modality when the other senses, such as vision and hearing, are absent. Defined by the Oxford English Dictionary, touch is “*the faculty of perception through physical contact*” [1]. Perception is a biological process through the sensory nervous system where external events are passed through the somatosensory cortex in the human brain that allows us to receive touch information.[14]

Haptics research is a multidisciplinary field combined with physiology, psychology, computer science and engineering, which is organized into four domains shown in Figure 1.1 [28]:

1. Perception and psychophysics
2. Human computer interface
3. Robotics
4. Virtual reality

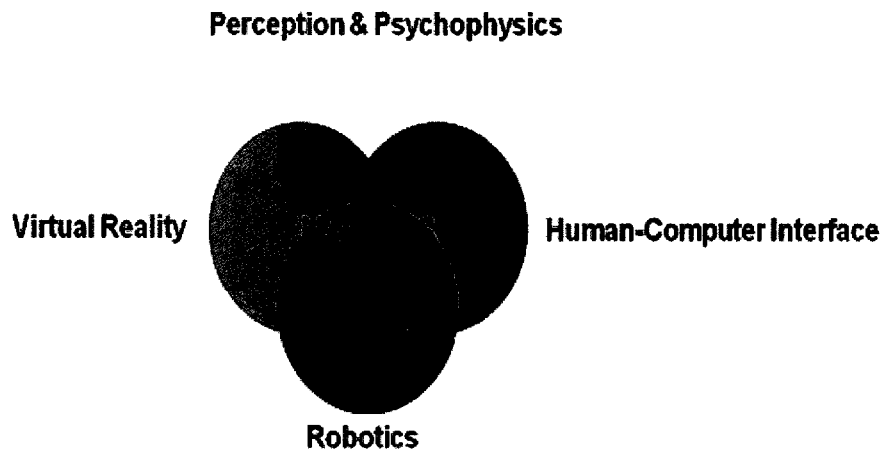


Figure 1.1: Four Domains of Haptics

In this research, the knowledge of the perception and psychophysics of haptics are examined to better understand the human tactile sensory system and develop perceptual tactile displays.

## 1.2 Motivation

The growing trend of multimodal human-computer interfaces has made it possible for the human body surface to be considered as an additional means of presenting haptic (touch) information using tactile and kinesthetic devices[41, 20]. The motivation of this research is due to the increase in demand for human-computer interaction (HCI) systems which has spurred research to improve the *sense of touch* using tactile devices. In earlier research, scientists and engineers attempted to replace vision systems for the blind with tactile systems, to provide verbal or situational information[45, 47]. Recently, tactile cues have been used for presenting extra information such as directional cues in a car[45], a grabbing force in tele-operation[35], a button pressing effect in a mobile device[16], tactile music[26], touch sensation in a remote interpersonal communication, etc[23]. More vibrotactile interfaces are now being integrated with human computer interaction systems and are becoming a popular research area, attracting tremendous demand in the entertainment, medical, military, art, education and e-commerce industries[41].

### 1.3 Existing Problems

Tactile devices are primarily composed of an array of actuators that consist of a broad range of tactile actuators, such as vibrating motors, electrodes, piezoelectric ceramics, pneumatic tubes, shape memory alloys, voice coils, etc. Limitations exist with tactile displays, in general, tactile actuators are of low resolution generating discrete stimuli due to:

1. Size of the actuators
2. Coarse sensitivity of two-point limen on the skin [12]

Therefore, in order to provide more apparent and subtle information with low resolution devices, researchers have aimed to display more detailed shape by using human sensory illusions [45, 33, 9, 46, 10]. Human sensory illusions are not merely visual, but occur in touch as well.[28] Sensory illusions take various forms, and may involve the perception of movement where no real motion over the skin exists [14]. For example, researcher in literature[9] developed a sensory aid display to deliver sensory illusions above an elbow amputee to transmit a continuous variable sensation on patients with prosthetic limbs. Researchers have extensively studied the factors which influence sensory illusions with vibrotactile displays, examining the spatial, temporal and intensity of the tactile stimulus. Such factors are explored to improve spatial information for the blind, the sense of touch for interpersonal communication systems and kinesthetic feedback for amputees[28, 23, 9]. However, this thesis focuses on investigating the factors of sensory illusions to display a dynamic tactile sensation, such as a smooth continuous sensation on the human skin, with discrete vibrotactile actuators.

### 1.4 Objective and Contribution

The objective of this thesis is numerated as follow:

1. Overcome the limitations of discrete vibrotactile actuators for low resolution tactile displays
2. Develop a wearable tactile display to present realistic human touch for HCI systems
3. Deliver tactile gestures, specifically to provide stroke movements on the human arm, thus the tactile stimulus needs to move continuously on the users' skin as shown in Figure 1.2



Figure 1.2: Stroke movement on the human dorsal forearm

The contribution of this thesis, presents the development and design of a wearable vibrotactile device using low resolution vibrotactile actuators to describe the transmission of a continuous movement with a human sensory phenomenon called the “funneling illusion.” The funnelling illusion is described as two equal intense stimuli which are presented simultaneously at adjacent locations on the skin; the perceived intensity is not felt separately but summed to form an illusion sensation midway between the two stimuli [10]. Funnelling illusion allows us to overcome the limitation of low resolution, tactile devices. Additionally, the design of a continuous movement algorithm and controlling algorithm are implemented to display the continuous, tactile movement on the human skin with the discrete actuators. In this work, after obtaining the illusion of a continuous movement of one tactile stimulus, we determined a high the quality of the continuous movement according to the effects of temporal intensity changes of the vibrotactile actuators in a linear and logarithmic pattern; location of the continuous movement on the dorsal of the human forearm and upper arm; orientation of the continuous movement with respect to the axis of the limb; duration of sensory excitation; and differences in gender. Psychophysical experiments have proven correlations between the orientation, distance, duration of the vibrotactile actuators and gender with the preferred intensity variation, substantiating our research direction to obtain a smooth, continuous movement sensation and enhance the quality for tactile displays.

## 1.5 Publications Resulting from this Research

The following four papers have been published. The first three are directly related to the thesis topic, while the last publication represents the direction of future research.

1. J. Cha, L. Rahal and A. El Saddik, "A pilot study on simulating continuous sensation with two vibrating motors," Haptic Audio visual Environments and Games, 2008. HAVE 2008. IEEE International Workshop, pp.143-147, Oct. 18-19, 2008.
2. L. Rahal, J. Kammerl, J. Cha, E. Steinbach, and A. El Saddik, "Investigating the Influence of Temporal Intensity Changes on Apparent Movement Phenomenon," IEEE International Conference on Virtual Environments, Human-Computer Interfaces and Measurement Systems (VECIMS), Hong Kong, China, May 11-13, 2009.
3. L. Rahal, J. Cha and A. El Saddik, "Continuous Tactile Perception for Vibrotactile Displays," IEEE International Workshop on Robotic and Sensors Environments (ROSE 2009), Lecco, Italy, Nov. 6-7, 2009.
4. M. Eid, J. Cha, L. Rahal and A. El Saddik, "Hugme: A haptic videoconferencing system for interpersonal communication," Proc. Int. Conf. Virtual Environments, Human-Computer Interfaces, and Measurement System (VECIMS), vol.178, 2008.

## 1.6 Thesis Organization

The remainder of this thesis is organized as follows:

**Chapter 2** presents an overview of background literature and related studies. Background concepts on tactile perception and the physiology of the human tactile senses are also introduced. It concludes with the exploration of work on human sensory illusions employed to mediate continuous tactile motion for vibrotactile displays.

**Chapter 3** discusses our proposed method to create the funnelling illusion, and elaborates on the system design phase. The design phase includes an overview of our dynamic vibrotactile system, technologies used to build the system and the control method implemented by Pulse-Width Modulation (PWM) to produce the intensity levels of stimuli.

**Chapter 4** focuses on the implementation process of our dynamic vibrotactile system. The systems architecture, which includes software and hardware architecture, is used to implement the vibrotactile system.

**Chapter 5** introduces four psychophysical experiments conducted to quantitatively and

qualitatively analyze the quality of the continuous movement and justify the suitability of our proposed method.

**Chapter 6** summarizes our overall work and includes a conclusion and discussion of potential future work.

# Chapter 2

## Background and Related Work

### 2.1 Literature Review

This thesis proposes a human sensory illusion to produce realistic continuous movement on the human skin with discrete vibrotactile actuators for wearable tactile displays. This chapter contains relevant information about tactile perception, addressing the history of tactile perception and related perceptual properties, such as tactile spatial sensitivity, temporal sensitivity and the physiology of the human tactile sensory system. Relevant information is used as guidelines to provide an awareness of human tactile senses in order to design perceptual tactile displays. This is followed by proposed approaches of sensory illusion phenomenon with associated controlled conditions, such as separation of the stimuli, orientations, relative amplitudes and temporal order, which influences human tactile senses in perceiving vibrotactile sensations.

Firstly, tactile perception and the physiology of human tactile senses are introduced; followed by the related work of sensory illusions employed to mediate continuous vibrotactile motion.

#### 2.1.1 Tactile Perception

Human perception has been examined since the early 19th century by Ernest Heinrich Weber, a German physiologist who derived the historically important law of sensation known as Weber-Fechner's Law. In 1834, Weber observed the human responses to physical stimuli. From his studies, he formulated Weber's law, stating that the change in a stimulus that will be just noticeable is a constant ratio of the original stimulus. Weber's student, Gustav Theodor Fechner, added to the law, deriving Weber's law into a loga-

rithmic relationship defining the perceived intensity of stimuli and the applied intensity of stimuli as logarithmic[37]:

$$F = a' \log I + b \quad (2.1)$$

Weber-Fechner's law from equation (2.1) defines F as the perceptual variable related to the stimulus, and I as the intensity of the stimulus, where a' and b are constants. As F is plotted against the logarithm of I, the expected result is linear. Thus, F legitimately quantifies human perception[37]. Over the years of physiological experiments, Weber-Fechner's law has been extremely useful in researching hearing, voice, light and touch for the development of haptic and perceptual displays[30]. In this thesis, we further investigate Weber-Fechner's law to provide continuous vibrotactile motion on human skin.

Optimizing human user interaction using perceptual tactile displays requires an understanding of the human sense of touch. The *sense of touch* is comprised of two distinct senses: tactile perception and kinesthetic perception. Tactile perception refers to the "*perception mediated by variations in cutaneous stimulation*"[40]. From this definition, the potential role of tactile perception is to provide awareness of stimulation on the human skin by means of skin receptors that lie within the skin. Conversely, kinesthetic perception provides awareness of static and dynamic human body posture and does not contribute to the cutaneous senses (skin receptors)[42].

Tactile perception is also referred to as *passive touch*, whereas kinesthetic perception is recognized as *active touch*. Studies on active and passive touch began in 1966 when J.J Gibson investigated the significance of touch[42]. Gibson and other researchers agreed that passive touch involves only the excitation of receptors in the skin[24].

Tactile perception has limited tactile pattern sensing capabilities with respect to its spatial sensitivity and temporal sensitivity. Spatial sensitivity and temporal sensitivity quantifies and transmits tactile information through the cutaneous senses. Spatial and temporal sensitivities are important factors in the design of vibrotactile displays. To provide optimal tactile information, such as continuous vibrotactile motion, the spatial and temporal parameters for our vibrotactile display must be equivalent to the spatial and temporal sensitivities of the cutaneous senses[42]. *Spatial sensitivity*, also known as spatial resolution or touch acuity, varies depending on the density of the cutaneous receptors. The fingertips, which have a high sensitivity density, can discriminate two

contacts at least 2.5mm apart. The palm however cannot discriminate two points less than 11mm apart; users feel only one contact point touching the skin. *Temporal sensitivity* is complemented by spatial sensitivity, in the sense that two contacts occur on the skin close in time[17].

Weber conducted the first psychophysical research on spatial sensitivity. He reported a number of studies of spatial resolution on several body areas that appeared to affect tactile sensitivity on the human skin. He also introduced the two-point limen technique, also known as the two-point threshold distance, which measures the minimal separation required to discriminate between one versus two contacts touching the skin[40]. Shown in Figure 2.1, the two-point threshold distance involves placing two sharp objects, such as points of a compass, on various parts of a human fingertip in order to find the threshold where a person can distinguish between the two points[17].

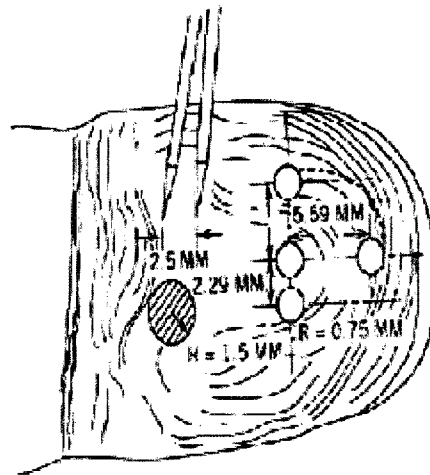


Figure 2.1: Four Domains of Haptics

Weinstein in 1968, further investigated Weber's two-point threshold distance and obtained data for the average spatial resolution found for men and women for the fingertip and other body sites, shown in Table 2.1.[14, 48]

Table 2.1: **Two-Point Threshold Distance On Several Body Sites**

Body Site	2-point Threshold Distance (mm)
Fingertip	2.5
Forearm	35
Upper arm	39
Torso	32-41
Back	70

Cholewiak et al. also investigated spatial sensitivity. The subjects were students aged 18 to 30 years old and spatial sensitivity was performed by vibrotactile experiments on the forearm, demonstrating that the percentages of tactile localization were between 72-82% at the elbow and wrist, and 45% at the dorsal of the arm, when the vibrotactile actuators are placed at 25mm apart. Cholewiak's experiments proved that an increase of vibrator separation from 25mm to 50mm increased recognition accuracy from 46% to 66%[19].

Thus, to generate optimum continuous vibrotactile motion, spatial sensitivity from Weinstien's and Cholewiak's data is taken into account in our work to estimate the optimum placement of the vibrotactile actuators on the human skin, such that users can perceive optimum continuous vibrotactile motion.

In the following section, the physiology of human skin is explained to better understand the modalities of the human sense of touch.

### 2.1.2 Anatomy and Physiology

Current research has explored the biological properties of human skin anatomy to investigate the human tactile sensory system in order to mediate the sense of touch. The design of perceptual tactile displays must satisfy human skin physiology.

Skin is the most versatile of all of the human body's organs; it is the largest organ, containing approximately  $1.8m^2$  surface area for the average adult[14]. Tactile perception is based on stimulating skin, which relates to understanding the sense organs of the tactile mechanoreceptors found in glabrous skin (hairless skin) and hairy skin. There are thousands of tactile receptors in human skin, allowing us to feel stimuli like pressure, vibration, pain, stretching, motion and temperature[17]. The cutaneous system (also known as the tactile system) refers to different receptors in the skin: temperature is

sensed by thermoreceptors, pain is sensed by nociceptors and deformation in the skin, such as vibration, pressure and stretching, are sensed by mechanoreceptors[25, 34].

Specifically researchers in vibrotactile stimulation have investigated the biological properties of tactile mechanoreceptors found in glabrous skin, which covers the skin of the palm of the hand, fingertips and sole of the foot. The glabrous skin has the highest density of cutaneous sensing. There are four major tactile mechanoreceptors found in the glabrous skin of humans: Meissner corpuscles, Pacinian corpuscles, Merkel disks and Ruffini endings, shown in Figure 2.2[25].

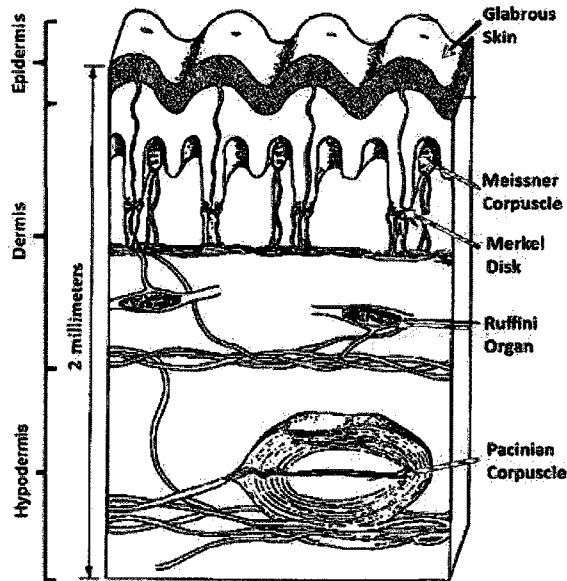


Figure 2.2: Cross-section of the human skin fingertip showing the location of the tactile mechanoreceptors[17]

Skin is made up of two distinct layers, shown in Figure 2.2: the *Epidermis* has a thickness that varies from 0.4mm to 1.6mm; the *Dermis* is 5 to 7 times thicker than the Epidermis, and is linked with the Hypodermis, the skin's last layer that connects the skin with muscle tissues, such as blood vessels and nerves[21].

The Meissner corpuscles, which sense velocity and provide information about movement across the skin, are located in the upper layer of the skin. The receptors have a

responsive frequency range at a low frequency of 20-50 Hz, and have a fast adaptation rate (FA-I) (ie. over time, we feel that we are no longer wearing glasses)[34]. The receptive fields for the Meissner corpuscles are small and well defined. Research has shown that receptors with small receptive fields will have high spatial resolution and receptors with large receptive fields will have low spatial resolution[21]. Thus, the Meissner corpuscles have high spatial resolution.

Pacinian corpuscles are the largest receptors in the skin, located deep in the skin and responsible for deep pressure touch, such as vibrations. The receptors detect high frequency ranges between 100-300 Hz. The receptors have a fast adaptation rate (FA-II) with large and indistinct receptive fields, thus having a low spatial resolution[21]. Also located near the surface of the skin are the Merkel disks, which are pain receptors that detect intensity and texture. These receptors have a slow adaptation rate (SA-I), which detects stimulus for a long time at a frequency range of 0-10Hz. Merkel disks have small receptive fields, with high spatial resolution[25].

The Ruffini organs are also located deep in the skin. These receptors detect skin stretch and have a responsive frequency range of 0-10Hz. The receptors detect a stimulus for a long time (SA-II) and have large and indistinct receptive fields, with low spatial resolution[17, 21].

As mentioned earlier, the biological properties of the cutaneous receptors are crucial in the design of tactile displays that factor in responsive frequency range, spatial resolution, receptive fields and adaptation rate. A summary of the biological properties of tactile mechanoreceptor fields is organized in Table 2.2.

Hairy skin covers much of the body, particularly the dorsal forearm, the dorsum of the hand and face. As shown in Table 2.2., hairy skin receptors have low spatial resolution; they thus do not effectively detect the specific geometric structure of a surface or object[27].

Tactile displays must truly reproduce, as closely as possible, the tactile characteristics of human skin receptors. Vibrotactile actuators must vibrate at maximum frequencies of around 100-300Hz to stimulate Pacinian corpuscles[21]. As a result, the threshold properties of all the mechanoreceptors are set as requirements for our tactile display.

Table 2.2: Tactile Mechanoreceptors and Corresponding Biological Properties[21, 27]

Mechanoreceptors	Skin Type	Sense Modality	Rate of Adaptation	Stimulus Frequency Range (Hz)	Receptive Fields	Spatial Resolution
Meissner Corpuscles	Glabrous	Velocity	FA-I (Fast adaptation rate with small receptive fields)	20-50	Small	Fair (3-5mm)
Pacinian Corpuscles	Glabrous and hairy	Pressure and Vibrations	FA-II (Fast adaptation rate with large receptive fields)	100-300	Large	Very Poor (2cm)
Merkel Disks	Glabrous	Intensity and Texture	SA-I (Slow adaptation rate with small receptive fields)	0-10	Small	High (0.5mm)
Ruffini Organs	Glabrous and hairy	Skin stretch	SA-II (Slow adaptation rate with large receptive fields)	0-10	Large	Poor (1cm)

The review in this section covers how tactile perception and sensory illusions deliver the *sense of touch* via continuous motion on the human skin. In the following section, an overview of the related work of human sensory illusions are presented, covering continuous vibrotactile sensations on the human skin.

## 2.2 Related Work

Psychophysical research recognized the need to integrate the properties of cutaneous senses into tactile interfaces to develop perceptual tactile displays[42].

The human sense of touch is part of the human perceptual system, which constitutes both tactile perception and kinesthetic perception. Tactile perception can be misinterpreted by human senses when misrepresentations of stimuli are presented; this is known as sensory illusion. Sensory illusions are perceptual mistakes discriminated by humans[14].

The oldest known sensory illusion of touch is known as the double sensation. Aristotle described this by crossing two adjacent fingers and then touching an object, such as a pen, with both crossed fingertips at the same time, feeling that two pens were touching his fingertips. Several other psychologists studied this ancient phenomenon to further investigate the influence of sensory illusions[14].

Psychophysical research in tactile perception has also investigated the phenomena of sensory illusions. Sensory illusions have been useful for the development of sensory-aid displays, tactile communication displays, haptic navigation displays and human-computer interfaces[45, 33, 9, 46, 10]. Related work involved with vibrotactile sensations with the development of dynamic vibrotactile displays are described in the following subsections.

### 2.2.1 Sensory Saltation

A common sensory illusion studied by vibrotactile researchers to employ vibrotactile motion is known as the sensory saltation phenomenon. Sensory saltation (*saltation*, meaning *jumping* in Latin) is a haptic spatiotemporal illusion, such that with correct spatial and timing parameters, a strong perception of directional lines will be perceived to the user. An example is shown in Figure 2.5.

Frank Geldard and his colleagues at the Princeton Cutaneous Communication Laboratory discovered the sensory saltation phenomenon, also known as the “cutaneous rabbit,” in the 1970s. Researchers have investigated sensory saltation to enhance vibrotactile displays particularly for spatial orientation for aviation and haptic navigation systems.[44]

## Haptic Navigation System

Tan et. al in 2003[45] studied the impact of sensory illusion on tactile situational awareness, useful for pilots, drivers or blind travelers. A haptic navigation system for attentional and directional cueing was developed to present haptic cues to a person's back with a 3x3 tactor array (tactors are also known as vibrotactile actuators), measuring the effectiveness of the user's spatial location awareness.

The haptic back display shown in Figure 2.3, consisted of a 3x3 vibrotactile array with an equal interstimulus distance of 8cm, integrated on the backrest of a chair.

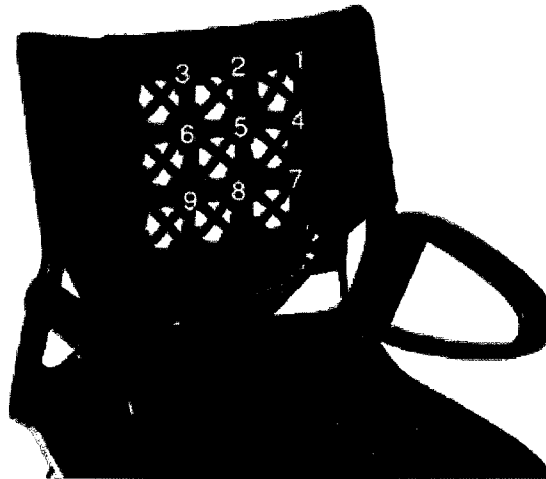


Figure 2.3: Haptic Back Display integrated with 3x3 tactor array separated at equal distances[45]

The hardware of the haptic back display consisted of:

- 3x3 tactor array made up of 40 mm diameter flat magnetic speakers
- Supporting fabric and elastic bands to place each tactor
- Audio power amplifiers to drive the speakers at a frequency range of 250-300 Hz
- PIC16C84 microcontroller to control pulse duration and inter-pulse interval

The controller circuitry was made up of the microcontroller and a nine-channel amplifier bank to precisely control the tactile patterns of the nine tactors in real time. Figure 2.4

shows the main components of the controller circuitry.

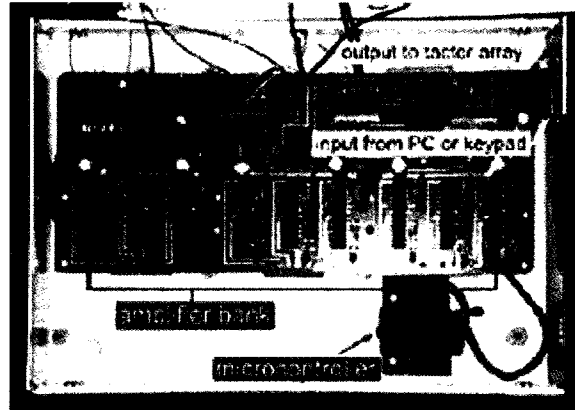


Figure 2.4: Controller circuitry[45]

The controller circuit receives input signals generated from a parallel port of a PC or keypad. The microcontroller then generates appropriate controlled signals to activate each tactor in a sequential time frame. These signals are sent to the amplifier bank, which amplifies oscillating output signals to the tactor array[45].

An example of sensory saltation is shown in Figure 2.5. Sensory saltation was demonstrated when three brief pulses were delivered to the first tactor, followed by three more pulses to the second tactor and one more pulse to the third tactor. The user had the impression that the sensation was discrete, as if tiny rabbits were crawling up the spine. Nonetheless, the user perceived discrete taps instead of a continuous sensation[45, 46].

Psychophysical experimental results show that judgments on the perceived line qualities were similar for different body sites (forearm, finger and back) and for the timing parameters. Furthermore, simultaneous activation of the tactors did not enhance the performance of the users[45].

Overall, sensory saltation is effective only in displaying discrete lines on the users' backs for haptic navigation displays. Sensory saltation has the potential to present vibrotactile movement for navigation and guidance displays; however, it does not correlate with our goal to provide a one tactile stimulus of a continuous movement.

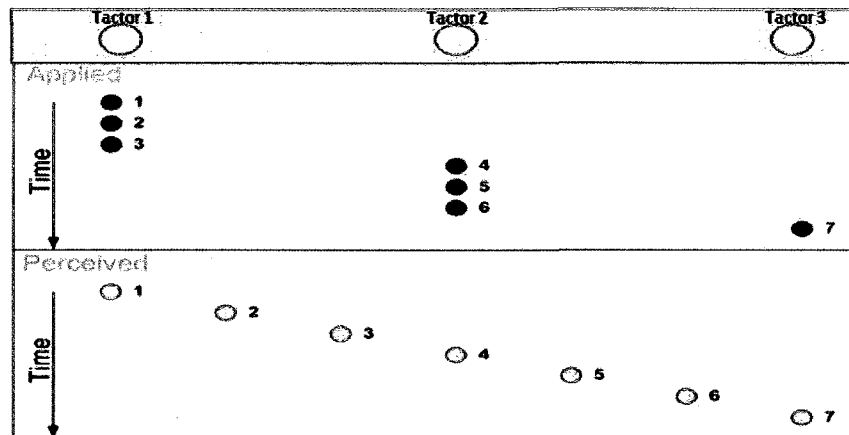


Figure 2.5: Illustration of the applied stimulation versus perceived sensation pattern for Sensory Saltation

In this work, we do not employ sensory saltation to display continuous vibrotactile motion since the sensation only provides a discrete vibrotactile movement instead of a continuous one. Further investigations of other sensory illusions is done in search of continuous vibrotactile movement.

### 2.2.2 Apparent Movement

Perceiving motion in our everyday environment is a common perceptual experience that triggers the somatosensory system in our brain, allowing us to feel motion and touch[17]. Apparent movement is a perceptual illusion which plays a prominent role in our lives not only through touch but through our visual system as well. For example, in the visual system, apparent movement occurs during a movie when discrete inputs, such as a series of sequential frames, are combined to create a smooth and continuous movie experience[14].

Similar to our visual system, apparent movement through touch creates a smooth and continuous motion on the skin using discrete signals. Studies of apparent movement have been used to enhance tactile communication displays for the speech and visually impaired[14]. Apparent movement occurs when two locations on the human skin are excited by two vibratory stimuli with a transient time delay; the user perceives an illusory sensation that continuously moves from the first stimuli location to the other[29].

Apparent movement is dependent on two temporal conditions: duration of the stimulus (DOS) and interstimulus onset interval (ISOI). Many researchers have tried to accomplish a ratio between the two duration parameters to display optimum apparent movement[29, 13]. DOS and ISOI is illustrated in Figure 2.6, where activating actuator A will vibrate first and actuator B will start to vibrate after a short interval, known as the ISOI. Both actuators vibrate for the same DOS[36].

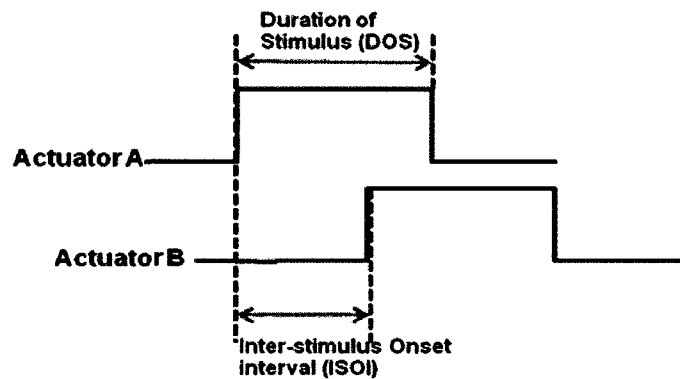
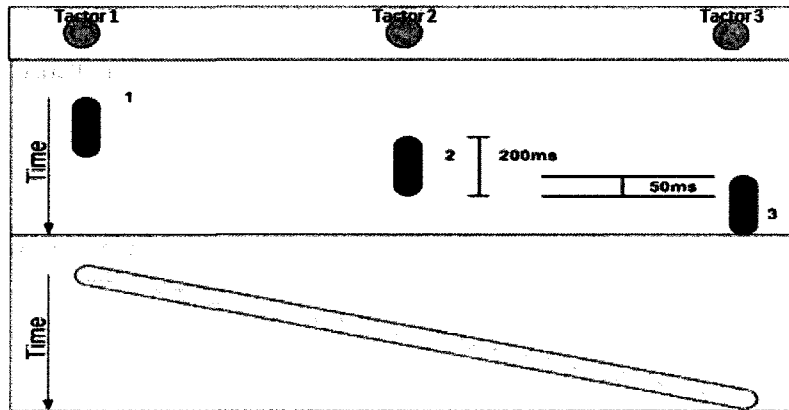


Figure 2.6: Illustration of DOS and ISOI[36]



Apparent movement, as sensory saltation is a spatiotemporal pattern which evokes a continuous tactile motion on the skin. For example, Figure 2.6 shows three factors activated with a DOS of 200 msec. Only factors 2 and 3 are activated with an ISOI for 50msec to produce a fast perceived continuous motion[13].

### **Effects of Stimulus Duration and Interstimulus onset intervals**

Apparent movement is also known as the “Phi phenomenon,” which has been studied by numerous psychologists since the 20th century to determine optimum temporal conditions for displaying continuous vibrotactile movement[13, 11, 29, 36, 43] .

In 1966, Sherrick and Rogers determined the optimal apparent movement illusion is the same functional relationship between DOS and ISOI with vibrotactile stimulators presented over the same temporal range of 100 to 400 msec on subjects’ thigh. Sherrick and Rogers, however, indicated that optimal ISOI does not exert a major influence on body sites [43].

Similarly, Gibson in 1963 also reported that ISOI had no significant effect on apparent movement, with a range of duration stimuli and the impressiveness of tactile apparent movement strongly influenced by both interstimulus distance and DOS[43].

Based on previous work, ISOI has no significant effect on apparent movement in this thesis, and we investigate only the perceptual parameters of interstimulus distance and DOS to display optimum continuous movement on human skin.

### **Vibrotactile Apparent Movement by DC Motors and Voice-coil Tactors**

In 2004, Niwa et al. in[36] investigated the effectiveness of the apparent movement illusion with two types of tactors: a DC vibrating motor and a voice-coil type tactor. The authors examined various tactile apparent movements to enhance the presentation of personal information with vibrotactile displays. They considered the cost and simplicity of the system, reducing the number of actuators while providing sufficient information with the vibrotactile display. They focused on tactile apparent movement displaying expressible information with a minimal number of actuators. This is interesting to note, as it reflects the guidelines of our approach in developing wearable vibrotactile displays.

The experiments conducted measured the perceived ratio of apparent movement for various DOS and stimulus onset asynchrony (SOA) parameters, also known as the ISOI. DCT shown in Figure 2.7 is a FM37E model DCT by Tokyo Parts Corp. The DCT generates vibration by rotating eccentric weights connected to a shaft of the DC motor

inside the DCT. The response time of the DCT is not quick, as it took more than 50msec to start vibrating and 60 msec to stop[36].

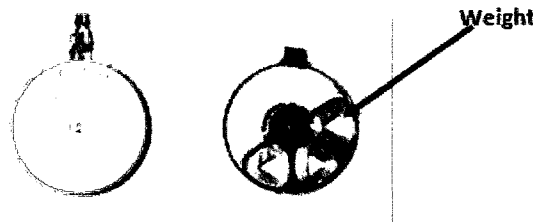


Figure 2.7: DC motor tactor (DCT)[36]

The VCT shown in Figure 2.8 is a MMA-33 VCT model by NEC Tokin Corp; it generates vibration based on weight reciprocation. The VCT is composed of a permanent magnet with a weight and is supported by a leaf spring. Vibration is generated as current is applied to the electromagnet and the permanent magnet becomes attracted to the electromagnet. However, when no current is applied, the permanent magnet is pulled back by the leaf spring[36]. Unlike DCT, VCT does not generate vibration with DC voltage; VCT is generated by pulse train signals. The advantage of VCT is its fast response time; it started vibrating immediately when the first input pulse signal was generated and stopped vibrating within 20 msec when the input signal was turned off[36].

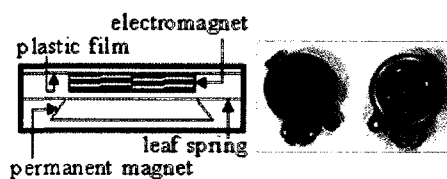


Figure 2.8: Voice coil tactor (VCT)[36]

The psychophysical experiments tested tactile apparent movement with two of the same types of tactors on the subjects' left arm. Shown in Figure 2.9, tactor A was placed on the lower arm while tactor B was placed on the upper arm, separated 70mm from the elbow. The tactors were connected to a PIC-16F873 microcontroller for control of sufficient timing for DOS and SOA intervals.

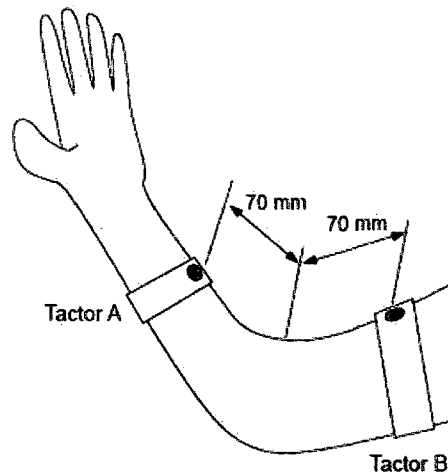


Figure 2.9: Localization of the two factors [36]

Results demonstrated that in regards to time factors for DCT inducing apparent movement, subjects favoured apparent movement when SOA and DOS values were similar. As for VCT, subjects could not discriminate apparent movement for an SOA greater than 400msec or less than 50msec. Only a few subjects were able to detect apparent movement when the values of DOS and SOA were similar. Significant results displayed for DCT showed that optimal SOA and DOS is between 100-200msec for the average subject to feel apparent movement. For VCT, the optimal SOA and DOS were at 200 msec for the average subject to feel apparent movement[36]. Overall, no significant difference was found between DOS and SOA, and thus optimum apparent movement is displayed for the same values of SOA and DOS for both DCT and VCT factors.

This report is a very encouraging example for the development of a wearable dynamic vibrotactile display, sharing the same motivations as our research in presenting continuous vibrotactile motion on human skin. However, in our approach, the DOS parameters are only taken into account for our proposed sensory illusion as there is no significant difference between ISOI and DOS parameters.

### **Apparent Movement Phenomenon using Shape Memory Alloys**

Mizukami et al.[33] researched apparent movement illusion in developing a tactile transmission system to display stroking or rubbing sensations on a user's palm. The tactile

display was developed as a sensory-aid for the handicapped.

The development of the tactile display consisted of shape-memory alloys (SMA) presenting a stroking sensation with an additional illusion known as the funnelling illusion, which they refer to as the phantom sensation (PS) and apparent movement phenomenon (AM).

The vibrotactile actuators were composed of a 5mm long SMA string with a diameter of 0.05 mm; its compactness was an advantage in displaying small stimuli on the palm. Shown in Figure 2.10, the activation of the SMA is driven by the pulse input signal current, which vibrates the SMA to allow the human to perceive the tactile illusion sensation, PS and AM. Pulse width modulation (PWM) control input signals of about 250Hz are generated in a PC to control the vibrations of the SMA actuators[33].

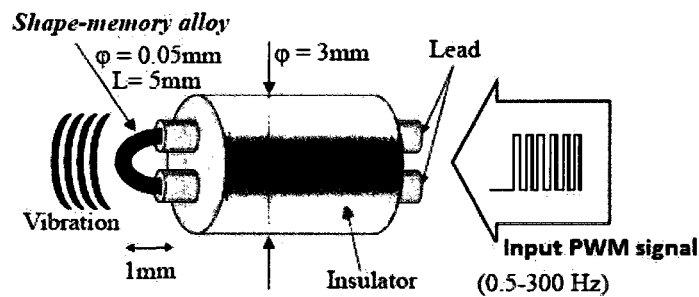


Figure 2.10: Illustration of the SMA driven by the PWM input signal[33]

The design of the tactility transmission system uses 8 SMA actuators displayed in a 3x3 array to present the phantom sensation and apparent movement phenomenon, as shown in Figure 2.11. The location of the AM are also shown in Figure 2.11, where the transmission of the movement will be displayed at the index, middle fingers and the palm, which provided the highest sensitivity to the sensation movement.

The transmission of the tactile sensation is illustrated in Figure 2.12, where the frequency and amplitude of the PWM input signal from a PC were fixed at 50 Hz and 0.75 volts with a varied duty cycle-ratio; this provided the highest sensitivity to the AM sensations based on the preliminary experiment. The PWM rectangular wave input signal is amplified to drive the two SMA actuators to display the PS and AM sensations.

Psychophysical experimental results showed that with a time delay of 100-700msec, most subjects felt the rubbed sensation on the palm and noted that the moving speed

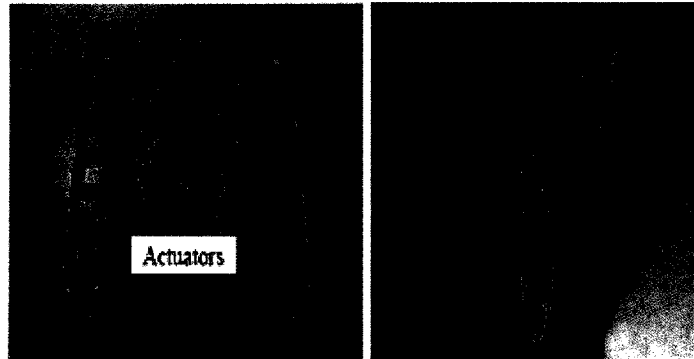


Figure 2.11: 3x3 SMA tactile display and Location of AM movement[33]

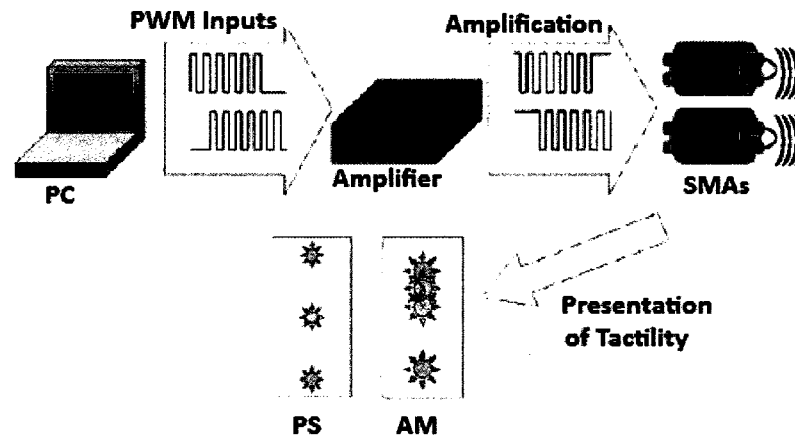


Figure 2.12: Illustration of the tactile information transmission using SMA [33]

of the sensation changes according to the time delay. With no time delay, the sensation appeared between the two vibratory stimuli. With a time delay of 100 msec, the sensation quickly moved from one location of the stimuli to the other. As the time delay increased, the speed of the sensation decreased at around 700 msec, and the sensation could not be perceived. In general, the speed of the sensation was too fast to display a continuous motion on the user's palm.

Making use of SMAs to present tactile sensations is advantageous for its compactness, quick response and low energy consumption. However, the ISOI of 100ms is judged to be quite short in feeling a rubbed sensation on the palm[33]. In our approach, we are more interested in displaying slow continuous sensations on the human skin. Nonetheless, with

all investigation of the ISOI on apparent movement, slow moving sensation cannot be simulated. As a result, to display slow continuous vibrotactile movement, we further investigate only the DOS parameter and an additional sensory illusion known as the funnelling illusion.

## 2.3 Funnelling Illusion

One of the supporting works we want to address is the sensory phenomenon of the funnelling illusion. The perceptual properties of the funnelling illusion investigated by Dr. Bekesy and Alles [11, 9] are highly considered in the development of our vibrotactile display, as the work closely reflects our design approach in producing a continuous vibrotactile movement.

### Funnelling Illusion by Dr. Georg von Bekesy

The ability to discriminate continuous tactile stimuli on the surface of the human skin has been studied using higher-psychological perception since the early 20th century. Dr. Georg von Bekesy, who received a Nobel Prize for his discoveries in sensory inhibition, proposed a human sensory illusion known as the funnelling illusion. Funnelling is a human sensory illusion describing a midway phantom sensation between multiple vibratory stimuli when they are presented simultaneously and separately at adjacent locations on the human skin [9]. In his 1958 work, Dr. Bekesy described the funnelling illusion as:

*“Both summation and inhibition vary with the amplitude of the vibration, the distance between the stimulated areas, the slope of the spatial distribution of the stimulus along the surface of the skin, its time pattern, and the density of the innervations. I have tried to describe these relations as variations in “funnelling action” of the nervous tissues”* [11].

Dr. Bekesy describes the funnelling illusion as two equal intense stimuli that are presented simultaneously at adjacent locations on the skin; the perceived intensity is not felt separately but summed to form an illusion sensation midway between the two stimulators. Dr. Bekesy describes the phenomenon as equivalent to directional hearing, where the funnelling illusion is affected by the separation of the stimuli, relative amplitudes and temporal order[11].

Dr. Bekesy also states that the funnelling illusion is influenced by the distance of separation between two alternately applied vibrations. Shown in Figure 2.13, if two vibrators were placed on the dorsal forearm of the human skin surface and were located close to one another at a distance,  $d_1$ , it is possible to produce a continuous sensation as the two vibrators switch for a small time delay of every  $1/4$  sec. However as the distance increases to  $d_2$  between the two vibrators, it is no longer possible to sum the two sensations into one continuous motion; rather, a discrete pulse sensation was felt, also as shown in Figure 2.13[11].

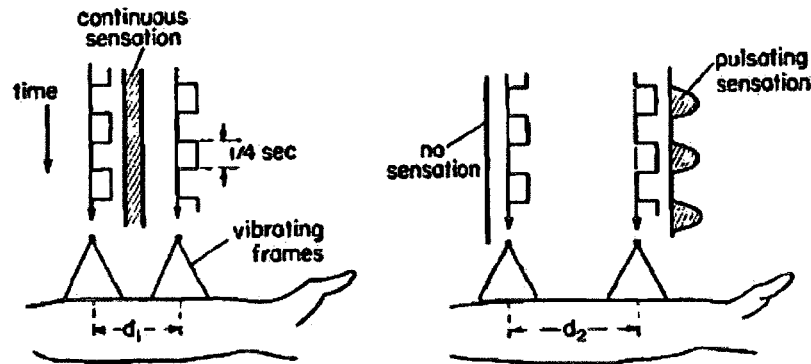


Figure 2.13: Continuous funnelling illusion for a small distance  $d_1$  and Pulsating sensation for large distance  $d_2$ [11]

It is of great interest for us to consider the funnelling effect with respect to the distance separation of the vibrotactile actuators located on the human skin to deliver continuous vibrotactile motion. Thus, the perceptual properties of the funnelling illusion investigated by Dr. Bekesy will be incorporated into our approach to simulate optimum continuous vibrotactile motion on the human skin.

### Information transmission by Phantom Sensation

In 1970, Alles[9] took advantage of the funnelling illusion proposed by Dr. Bekesy to improve sensory-aids displays, describing the illusion as the phantom sensation phenomenon. The funnelling illusion was utilized to provide kinesthetic information to an above-elbow amputee and was chosen to provide a continuously variable sensation with a minimum of hardware.

The location of the continuous vibrotactile sensation varied with the angle of the prosthesis elbow. As the elbow was extended, the sensation occurred near the end of the remaining upper arm; as the elbow was flexed, the sensation progressed up the arm. Only two stimulators were required to provide a continuous variable sensation, minimizing the use of hardware.

The Funnelling illusion described in Alles is illustrated in Figure 2.14(a), below. The ellipse at the first layer shows the location and intensity of the two tactile stimuli. At the lower layer, the larger ellipse corresponds to the midway sensation based on the intensity ratio of the two applied tactile stimuli. Two tactile stimuli are funnelled into

one midway sensation and the perceived intensity relates to the summation of the two intensities applied on the human skin. As proposed in Dr. Bekesy's quote, the location of the funnelled sensation can be modified in two ways: temporal inhibition and amplitude inhibition.

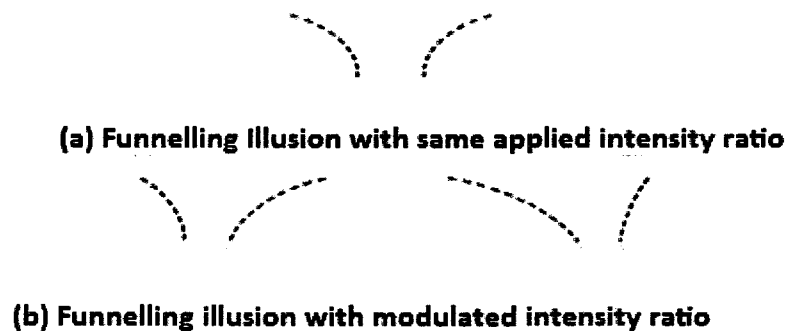


Figure 2.14: Illustration of the Funnelling Illusion

**Temporal inhibition** adjusts the interstimulus time interval of the stimuli. Temporal inhibition occurs as the activity of the vibrotactile actuators are activated at different time intervals in a particular pattern with the same intensity or same loudness of vibrations as described by Alles[9]. The perceived location moves towards the earlier stimulus. However, when the time interval goes over a certain vibrotactile threshold, the funnelling illusion disappears and the two stimuli are felt separately.

**Amplitude inhibition** applies when the activity of the vibrotactile actuators are activated at the same time, as shown in Figure 2.14(b). The presented stimuli are funnelled and the perceived stimulus locates towards the actuator with the higher intensity ratio or also referred as the loudest vibration. In this paper, we exploit the amplitude inhibition phenomenon to create the continuous vibrotactile movement, as it can produce a stronger funnelling illusion compared to the temporal inhibition proven by Alles[9].

Additionally, Alles reported that in inheriting amplitude inhibition, the intensity of two tactile stimuli can be varied linearly and logarithmically to provide continuous vibrotactile motion. However, logarithmic variation intensity must be applied to the two tactile stimuli, rather than linear variation intensity, in order to perceive the continuous movement sensation as equally intense along the movement path.

Shown in Figure 2.15 for linear intensity variation, if the amplitudes of the two tactile stimuli vary linearly, the perceived sensation of the loudness will become faint near the

midpoint between the two actuators. For logarithmic intensity variation, shown in the right figure, if the amplitudes of the two tactile stimuli are varied logarithmically, the perceived sensation of the loudness will appear equally intense along the movement path.

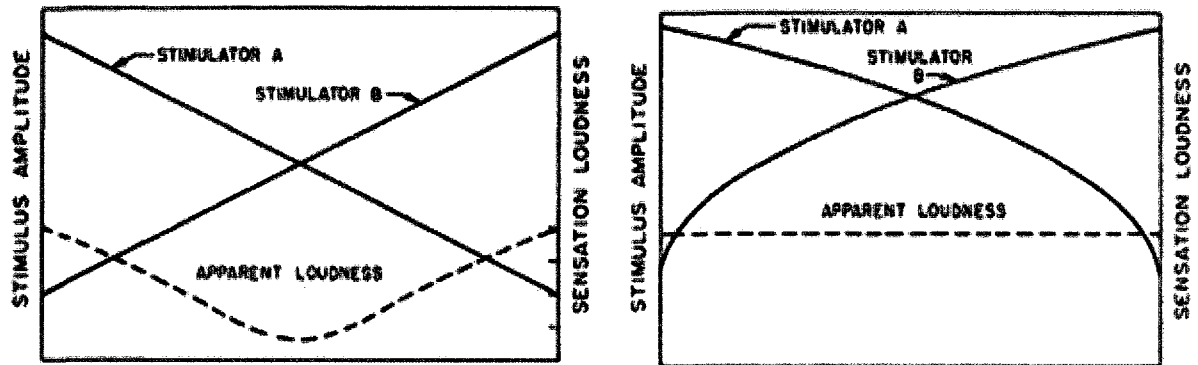


Figure 2.15: Linear intensity variation produces a perceived continuous sensation of the loudness to be faint at the midpoint between stimulator A and stimulator B. In the right figure, a logarithmic intensity variation produces a perceived continuous sensation of the loudness to be equally intense between stimulator A and stimulator B[9]

Alles reports a number of perceptual properties similar to Dr. Bekesy that affect the influence of the funnelling illusion, which can be useful in our work for obtaining optimum continuous vibrotactile movement:

- Amplitude Variation:
  - o Funnelling illusion produced by amplitude inhibition alone is as good as producing both amplitude inhibition and time-delay variation and is much more distinct than producing time delay alone.
  - o Logarithmic variation provides an equal intensity funnelling illusion.
  - o Linear variation decreases the funnelling illusion at the midpoint between the two stimulators.
- Size of the stimulators: Size of the stimulators is influenced by the requirements of the funnelling illusion and the physiological properties of the human skin.
- Spacing of the stimulators: Optimum distance between two stimulators is dependent on the information transmission of the funnelling illusion, which degrades with increasing display length.

- Direction of motion: Stimulators tangential to the skin's surface defines a better distinct sensation than stimulators normal to the surface of the skin. Dr. Bekesy reported the same as the funnelling illusion is superior when tangential stimuli at zero degree angles are excited on the skin.
- Location of the stimulators: Stimulators should not be placed on an area directly over the joint, which can transmit vibration through the bone
- Temporal variations: 100 Hz repetition rate provides a distinct funnelling illusion, but the sensation was too rapid

The perceptual parameters addressed by Alles were applied to non-amputee subjects to display the funnelling illusion on the upper arm. The funnelling illusion was transmitted from the upper arm to the subject's elbow. Subjects reported that the funnelling illusion was easily detected and provided a valuable kinesthetic feedback as a sensory-aid display for patients with prosthetic limbs.

In our presented work, we further investigate the influence of amplitude inhibition on funnelling illusion quality by making use of linear and logarithmic intensity variations to display continuous vibrotactile sensation on the human skin.

Dr. Bekesy's and Alles's investigations on the perceptual parameters for displaying the funnelling illusion are essential and act as potential guidelines for our approach to obtain optimum continuous vibrotactile motion.

### **2.3.1 Comparison**

An overview of this chapter illustrated the design principles of human sensory illusions and the previous work involved in presenting dynamic tactile motion with vibrotactile displays. The chapter also highlighted the perceptual features of the sensory illusions, such as spatial sensitivity, temporal sensitivity, amplitude variation, frequency sensitivity, body site and the type of vibrotactile actuators.

A classification of the different approaches of sensory illusions with associated vibrotactile display is summarized in Table 2.3.

The different approaches of the tactile sensory illusions with their perceptual features will provide guidelines for this research in displaying optimum continuous vibrotactile

Table 2.3: Summary of Perceptual Features in Tactile Sensory Illusions

Sensory Illusion	Vibrotactile Display	Application	Body Site	Temporal Sensitivity	Amplitude Variation	Spatial Sensitivity	Frequency Sensitivity	Vibrotactile Actuator
Sensory saltation	Haptic Back Display[45]	Navigation guidance system	Back	ISOI=50 msec	Not applicable	80 mm	300 Hz	3x3 array of flat magnetic speakers
Apparent movement	Tactile personal information[36]	Wearable vibrotactile display	Upper arm and forearm	DOS=ISOI for 100-200msec	Not applicable	70 mm	VCT:150 Hz DCT:200Hz	DCT and VCT
Phantom Sensation and Apparent movement	Palm sized vibrotactile display[33]	Sensory aid for handicap	Palm	ISOI=100msec	Not applicable	3 mm	250 Hz	3x3 array of Shape memory alloys
Funnelling illusion	Kinesthetic feedback display[9]	Sensory aid for amputees	Upper arm	Not applicable	Logarithmic and Linear	4 to 5 inches	100 Hz	Two cylindrical vibro-stimulators

motion.

Our approach to display dynamic continuous tactile motion with sensory illusions will lead to a reduction of hardware for wearable vibrotactile displays while transmitting distinct and high resolution tactile information. The continuous sensation will be highly beneficial for vibrotactile displays intended for impaired users, navigational or directional information, mobile computing and human-computer interactions. Our approach will consider the perceptual features as control conditions to present optimum continuous vibrotactile movement along human skin.

# Chapter 3

## Proposed Method

This chapter focuses on the proposed method of our work: to overcome the limitations of discrete vibrotactile displays to replicate the “sense of touch.” Human sensory illusions are created with low resolution vibrotactile actuator arrays to produce a smooth, continuous movement sensation on the human skin. The first half of this chapter describes our proposed continuous sensation, and the second half provides an overview of the vibrotactile system and technologies used in its construction.

### 3.1 Proposed Continuous Movement Sensation

The objective of our research is to present a dynamic tactile sensation, such as a continuous sensation for low resolution vibrotactile displays. Specifically, we would like to develop a wearable tactile display to deliver realistic tactile gestures, such as a stroke movement on the human arm for the use of HCI systems. The above objective is achieved by making use of a human sensory illusion to display a continuous movement on the human skin with discrete vibrotactile actuators. Additionally, the design of a wearable vibrotactile device with the implementation of the continuous movement algorithm are implemented to provide a tactile, continuous movement sensation.

Alternative designs to present tactile movement sensation with vibrotactile displays have been proposed by previous researchers from literatures [45, 33, 9, 46, 10] see summary table 2.3 in section 2.3.1 for further information. Tan et al. [45] studied the impact of “sensory saltation”, also known as ‘cutaneous rabbit’, by presenting directional information on the back of a human body with a 3 by 3 vibrotactile array. Users perceived

discrete taps instead of a continuous sensation. Additionally, Mizukami et al. [33] researched “apparent movement” illusion by developing a tactile transmission system to display stroking sensations on a user’s palm. Apparent movement, was demonstrated as two locations on the human skin are excited by two vibratory stimuli with a transient time delay, the user perceived an illusory sensation which continuously moves from the first stimuli location to the other. However, the time delay was too short, for example, at around 100ms in order to perceive a rubbed sensation on the palm. In general, the speed of the sensation was too fast to display a continuous motion on the user’s palm.

In our proposed method, however, to deliver slow and smooth continuous movement, we exploit the human sensory illusion of the “funnelling illusion” investigated by the works of Dr. Bekesy and Alles [10, 19]. The psychophysical effect is displayed by amplitude inhibition related to the funnelling illusion, illustrated by Alles in Section 2.3. Based on the work of Alles, amplitude inhibition has proven to provide more effective results to display the funnelling continuous movement compared to temporal inhibition. As a result we investigate, amplitude inhibition to present continuous movement on the human skin. We control the intensity of the adjacent vibrotactile actuators in a linear and logarithmic variation to display a continuous moving sensation along the range of stimulation. An illustration of our proposed approach is described in Figure 3.1.

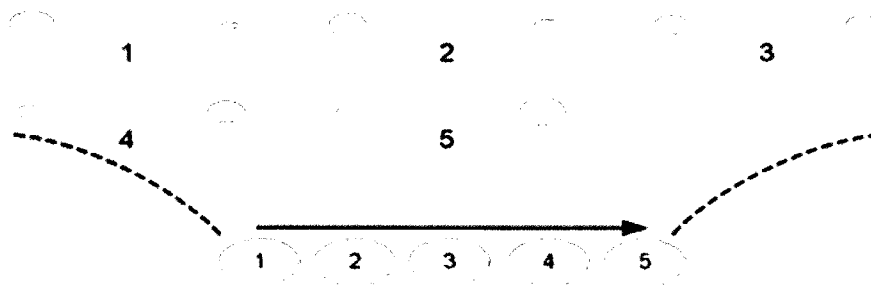


Figure 3.1: Illustration of our proposed continuous movement sensation by exploiting the funnelling illusion. The numbers denote the discrete steps which are successively applied.

We propose to vary the intensities of adjacent tactile stimuli with inverse proportional intensities. In other words, one tactile stimulus' intensity will ascend from a small to large intensity level while the other tactile stimulus will descend from a large to a small intensity level. Therefore, the resultant, perceived sensation will move continuously from the left stimulus location to the right. The discrete, perceived stimulus however will be felt as one continuously moving stimulus, as shown in Figure 3.1.

Based on the psychophysical effect of amplitude inhibition related to the funnelling illusion, we are able to deploy a continuously moving vibrotactile sensation along the human skin. From previous literature[9], it is known that the quality of the presented continuous movement sensation depends on a linear and logarithmic intensity variation when cross fading from one actuator to another. In the following section, we describe the formulas used to display the linear and logarithmic intensity variation.

### 3.1.1 Continuous Movement Formulation

In the literature[9] address the linear variation of stimulus amplitudes, which cause the funnelling illusion to fade near the midpoint between two stimulators. Alles found that the logarithmic variation of the stimulus amplitudes also cause the funnelling sensation to appear equally intense throughout the stimulus location. Equations (3.1) and (3.2) are the linear and logarithmic intensity variations, respectively, which are formulated based on Alles' proposed methodology.

$$I(t) = (t/t_{max}) * \eta \quad (3.1)$$

$$I(t) = \log(1 + t * c) / \log(1 + t_{max} * c) * \eta \quad (3.2)$$

$I(t)$  is the intensity variation function at a given time  $t$  where  $c$  is a constant that controls the log intensity and  $\eta$  is the level of applied intensity,  $0 \leq \eta \leq \eta_{max}$ . Where the  $a(t)^{ith}$  actuator is activated  $a(t) = a_1(t) \dots a_i(t)$ ,  $a_i \in [0,1]$ . Each actuator has two activation states, 1=ON and 0=OFF.

We further investigate Alles' proposed methodology on amplitude inhibition to display a continuous movement sensation on the human skin. In previous research[9, 33] the continuous movement has been established for varying distances and temporal changes. In our work, we examine the quality of the continuous movement based on the influences of the control conditions. These control conditions are two temporal, linear and logarithmic intensity change functions, which are evaluated with respect to varying distances, orientations and temporal order of the vibrotactile actuators.

## 3.2 Overview of the Vibrotactile Device

We have designed a dynamic, vibrotactile display for use in multimodal human-computer interfaces. Vibrotactile cue devices are associated with an array of vibrotactile actuators which are of low resolution, due to the size of the actuators and the coarse sensitivity of two-point limen on the skin[17]. In general, tactile devices are composed of a broad range of tactile actuators, such as vibrating motors, electrodes, piezoelectric ceramics, pneumatic tubes, shape memory alloys, voice coils, etc[12]. The following sections discuss the specific technologies used to implement the dynamic, wearable tactile display.

### 3.2.1 Vibrotactile Actuators

In our work, we chose pancake-type vibrating DC motors usually found in cell phones to act as vibrotactile actuators and provide the *sense of touch* to users. The disk-shaped pancake motor produces vibrations by rotating a mass in a plane parallel to the mounting surface[3].

Based on prior research[9, 11], we knew the direction of the motion of the pancake DC motors must be tangential to the surface of the skin to display the funnelling effect. Shown in Figure 3.2, the pancake DC motors from Precision Microdrives™ has a diameter of 10mm and 3mm in height. The DC motors has an operating voltage range of 2.5-3.8V and operating frequency of 220Hz which is adequate to produce vibrations on the skin for tactile feedback as described in section 2.1.2[17].



Figure 3.2: Single Vibrotactile Actuator[3]

The small, vibrotactile actuators have useful properties for our tactile device: they are inexpensive, have small power consumption and are easy to implement (which is productive for marketing into any wearable tactile displays). Moreover, the actuators

are very light-weight, weighing 1 gram and still producing adequate vibrations on the wearer. The small size of the actuators is essential to fit in a thin, dynamic workspace of any textile material. The small form factor also makes the actuators invisible to the user until a stimulus occurs. Additionally, in our research we have used ribbon cables for the wiring of the actuators. These ribbon cables provide high flexibility and minimizes current conductivity passing through the thin wires where the current consumption is within a reasonable range. A major design requirement that will ensure safety and optimal comfort to the user.

Advanced conductive wiring has been used for in the latest research in wearable tactile displays. Materials like metallic silk organza and conductive yarns can be easily sewn into wearable material with electronic devices[32]. These advancements will be taken into consideration as future requirements for our wearable tactile display.

Also shown in Figure 3.2, each vibrotactile actuator are attached and detached on flexible armband straps through Velcro material that are separated by specific distances. The location of the actuators can be freely changed for experiments to determine the distance sensitivity of the funnelling effect. The armband straps are made from nylon which makes it a flexible, elastic, tight material such that the vibrotactile actuators attached on the Velcro of the armband straps will be placed comfortably on the skin of the subjects. This will ensure a strong vibrotactile sensation from the funnelling illusion as the armband straps are wrapped around comfortably on subjects' upper limb (i.e.: forearm and upper arm).

Illustrated in Figure 3.3, the orientation of the funnelling illusion can be displayed along the transverse and longitudinal directions. The transverse direction is presented with adjacent actuators placed on one armband strap, whereas for the longitudinal direction, each actuator is placed on separate armband straps. These configurations will allow us to determine the quality of the continuous movement sensation along various orientations and distances.

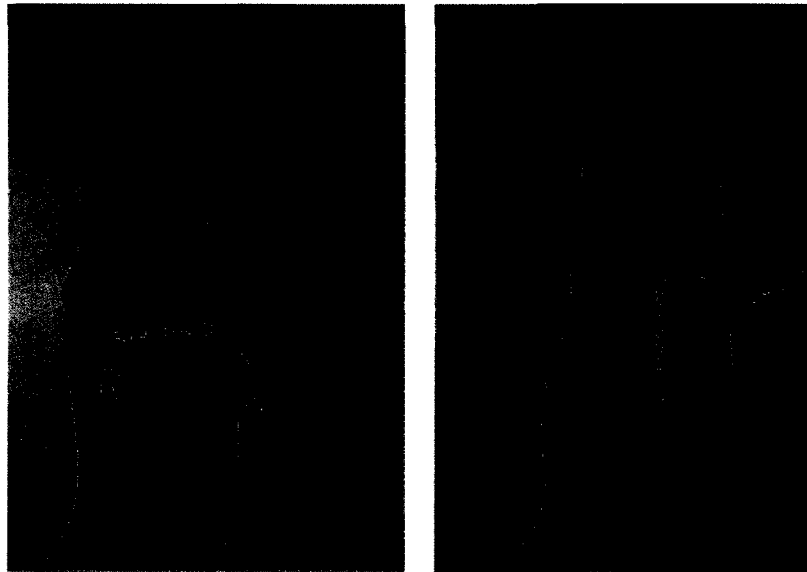


Figure 3.3: Transverse Orientation and Longitudinal Orientation

### 3.2.2 Microcontroller

The brain of our dynamic vibrotactile display was established by a 16MHz ATmega128 microcontroller an Atmel AVR family. The MCU is integrated onto an ET-AVR Stamp module by Futurlec Inc. shown in Figure 3.4[2]. The miniature stamp board provides various functionalities such as performing fast and easy downloading, wireless and serial communication. As well it includes large numbers of I/O ports, a total of 56 digital output lines each of which can be used to drive a single vibrotactile actuator. Critical in the future design of the wearable tactile display where many electrical devices, actuators and sensor will be integrated to advance the design of the circuit.

Additional design alternatives for the ATmega128 MCU has been considered with the Microchip microcontroller dsPIC30F2012, however the MCU contains a maximum of 10 I/O ports which is not suitable in the design for integrating multiple electronic components. Considering the risk analysis of our system design, the dsPIC30F2012 maximum current consumption is 25 mA which is not adequate to activate the actuators which require a maximum current consumption of 85 mA to function properly. Whereas, the ATmega128 provides a maximum current consumption of 100mA which delivers suitability for driving the actuators and a safety current consumption range.

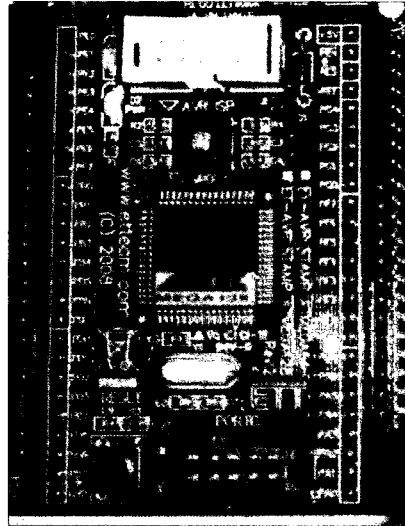


Figure 3.4: ATmega128 MCU on ET-AVR Stamp Board[2]

Additionally, for future design advancements we will investigate flexible microcontrollers to provide flexibility into wearable materials. In addition to its other features, the AT-Mega128 with a 5V operating voltage has highly flexible power management capabilities that were used in implementing the vibrotactile system. This makes it a very applicable unit for prototyping wearable vibrotactile displays.

### Controlling Mechanism

The microcontroller adjusts the intensity of the vibrotactile actuators by communicating within the same rate (57 Kbaud rate) of a RS232 serial link with a host PC to transfer the tactile control data. The intensity of the actuators is controlled by a pulse width modulation (PWM) algorithm. A logic loop of PWM binary signals provided each vibrotactile actuator with 16 levels of applied intensity using the digital PWM signals, shown in Table 3.1.

Table 3.1: PWM signal corresponding to the level of applied intensity

Level of Applied Intensity	Digital PWM signal
0	000000000000000000
1	111110000000000000
2	111111000000000000
3	111111100000000000
4	111111110000000000
5	111111111000000000
6	111111111100000000
7	111111111110000000
8	111111111111000000
9	111111111111100000
10	111111111111110000
11	111111111111111000
12	111111111111111100
13	111111111111111110
14	1111111111111111110
15	1111111111111111111

The minimum applied intensity labelled with '1' is set as the minimum intensity a human can perceive the applied intensity. The applied intensity labelled '0' means the actuator is off and the maximum intensity labelled with '15' is set as the maximum applied intensity the actuator can produce at 3.8 volts. The PWM technique enabled our team to vary the frequency of the applied intensities, which in return varies the magnitude of the vibration being produced, and controls the vibrations of the DC vibrotactile actuators.

Below, shown in Figure 3.5 is a MCU state machine diagram illustrating the high level behaviour of our dynamic vibrotactile system:

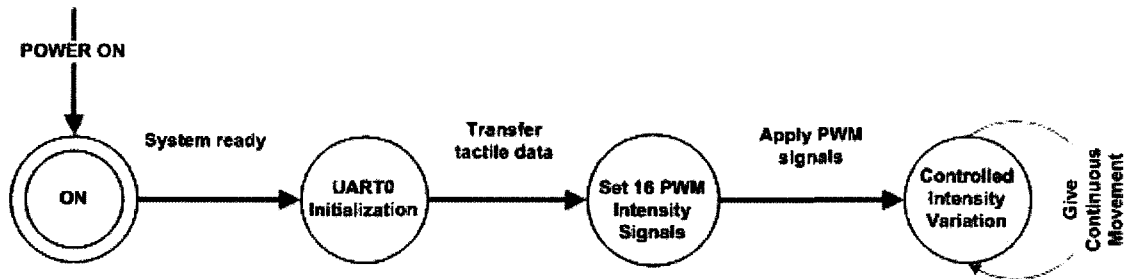


Figure 3.5: High Level of the MCU State Machine

The dynamic vibrotactile system was developed to control the applied intensities of the vibrotactile actuators by a set of 16 level of PWM signals in response to commands received from the RS232 link via UART0 com port with the host PC. Microsoft Visual Studio C++ was used on the host PC to deliver the commands of the continuous movement algorithm, which is either logarithmic or a linear algorithm. The applied controlled intensity signals are sent to the actuators to display a continuous movement sensation on the user.

### 3.3 Overall System Design

Figure 3.6 provides an overview of the various components used to make up our dynamic vibrotactile system. The vibrotactile system receives commands form a host PC through a standard serial interface and controls the intensity of the DC vibrotactile actuators.

Our controller prototype was the ATMega128 microprocessor to control the intensity of each vibrotactile actuator by PWM. An external 9V DC power supply is connected with voltage regulator (LM7805) to provide 5V DC to the MCU and the RS232 serial port connector. Despite the simplicity of our controlled design, the system is useful for a variety of applications regarding low-resolution DC actuators.

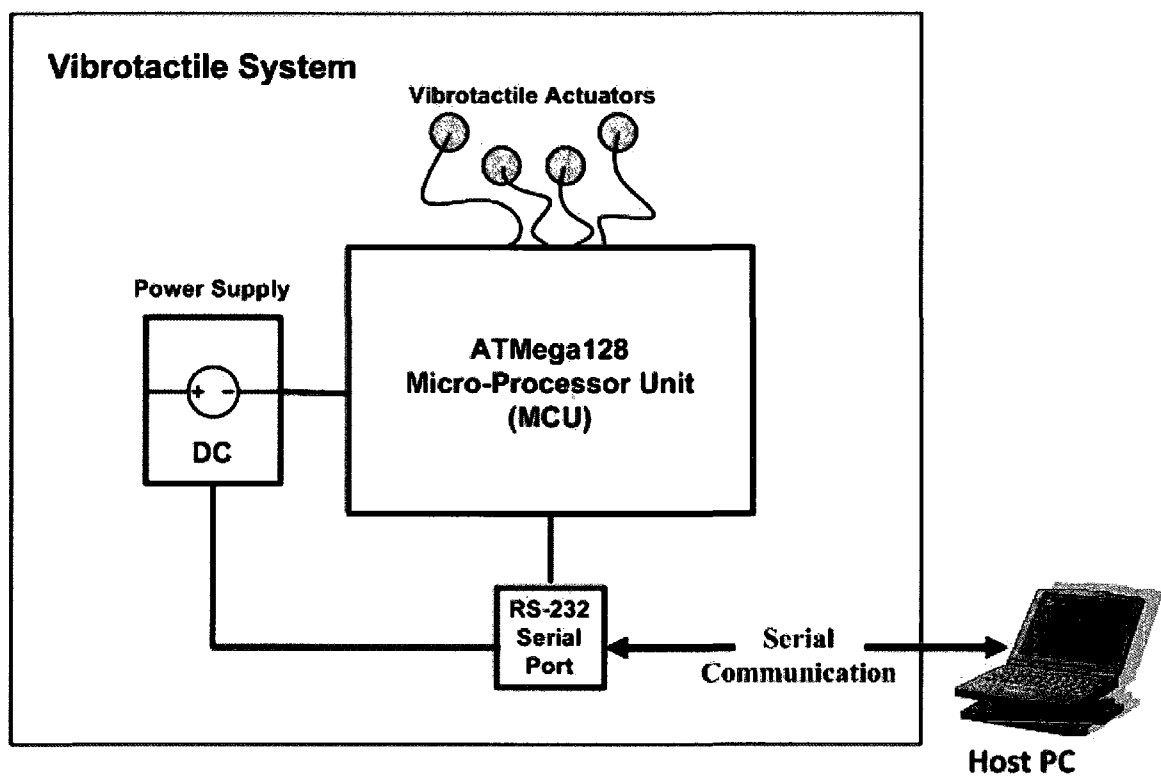


Figure 3.6: Dynamic Vibrotactile System Overview

# Chapter 4

## Implementation

In this chapter, we will review the implementation process of our dynamic vibrotactile system using the design concepts described in the previous chapter. The following sections discuss in detail the systems architecture and models used to implement the vibrotactile system.

### 4.1 System Architecture

In this section, we explore the approach considered for the architecture of our dynamic vibrotactile system. The architecture of our system consists of two design approaches: the hardware design and software design. The main components of the hardware design consist of the ATmega128 MCU, power supply and the vibrotactile actuators; the software design is composed of a host driver running on the host PC, and a PWM controller running on the MCU. We implemented two software designs: in our first design the host PC sends commands to the MCU to indicate the applied intensity variation, and in the second the MCU uses pulse width modulation (PWM) to control the vibrotactile actuators at the desired intensity levels similar as in [15]. The following sections discuss the models used in the implementation of the software and hardware architecture such as the control software architecture, host driver architecture, continuous movement algorithm, circuit diagram and controlling algorithm.

## 4.2 Software Architecture

The following subsections discuss the software implementation designs of the vibrotactile system.

### 4.2.1 Control Software Architecture

Many controllers have been designed for tactile displays to control the activation of electronic elements such as voice coil factors, pneumatic actuators, and pager motors. Our design goal for our controller is to have the ATmega128 MCU control the level of intensities of multiple vibrotactile actuators by using the PWM technique. PWM will allow us to control the duration of the applied intensities, which in turn will control the vibrations produced by the vibrotactile actuators. The duration of the PWM signal is controlled by varying the time of the duty cycle of the signal. The duty cycle of the signal is the portion of time during which the vibrotactile actuators are operated, thus the time when the signal is high (logic 1)[8]. By varying the signal's duty cycle will increase or decrease the intensity of the vibrotactile actuators.

Shown in Figure 4.1, is a flow chart illustrating the control software architecture of our system. Two software designs were implemented for our system: first, the host PC software, implemented in Microsoft Visual Studio C++ has a host driver running on a PC sending out byte commands to the MCU to indicate whether the applied intensity variation is linear (logic 0) or logarithmic (logic 1). The MCU software, implemented in WinAVR C language, uses a set of 16 levels of PWM binary signals where the duty cycle of the signal will be set as high (logic 1) or low (logic 0) to vary intensity levels. The PWM signals will be sent as 8 control bits to the MCU output ports, activating the controlled vibrotactile actuators.

## 4.2.2 Host Driver Architecture

The host PC, runs a host driver algorithm implemented in Microsoft Visual Studio C++ where multiple classes are used to ensure that the velocities, durations, distances and linear or logarithmic applied intensity variations are sent over the serial communication to the MCU of the vibrotactile system. The classes were characterized as, LogParameterAdjust, LogParameterAdjustDlg, TactileArray, Serial port, PilotDlg and PersonalInfo.

Shown in Figure 4.2, is a flow chart diagram outlining the algorithm of the host driver software.

The top level entity in the Visual Studio C++ application, called LogParameterAdjust.sln, is the LogParameterAdjust class. The LogParameterAdjust class manages the user interface and handles the LogParameterAdjustDlg class. Moreover, the LogParameterAdjustDlg class implements two interfaces: PersonalInfo() for receiving incoming data such as the users Gender() and Age() from the PersonalInfo class, and also PilotStudy() for receiving incoming data such as the intensity Velocity(), Distance(), Duration(), NumActuator() and LogParameter() from the PilotDlg class. Tactile Array class manages the serial port connection to the vibrotactile device. Additionally, it controls the communication protocol by calling the SerialPort() function from the SerialPort threaded class to send the incoming data Intensity() function which is either a logic 0 or logic 1. The functions Intensity(), Velocity(), Distance(), Duration() and LogParameter() are packaged and are sent over the serial communication link at a 57 Kbaud rate, where the tactile data is sent to the serial port and then forwarded to the MCU.

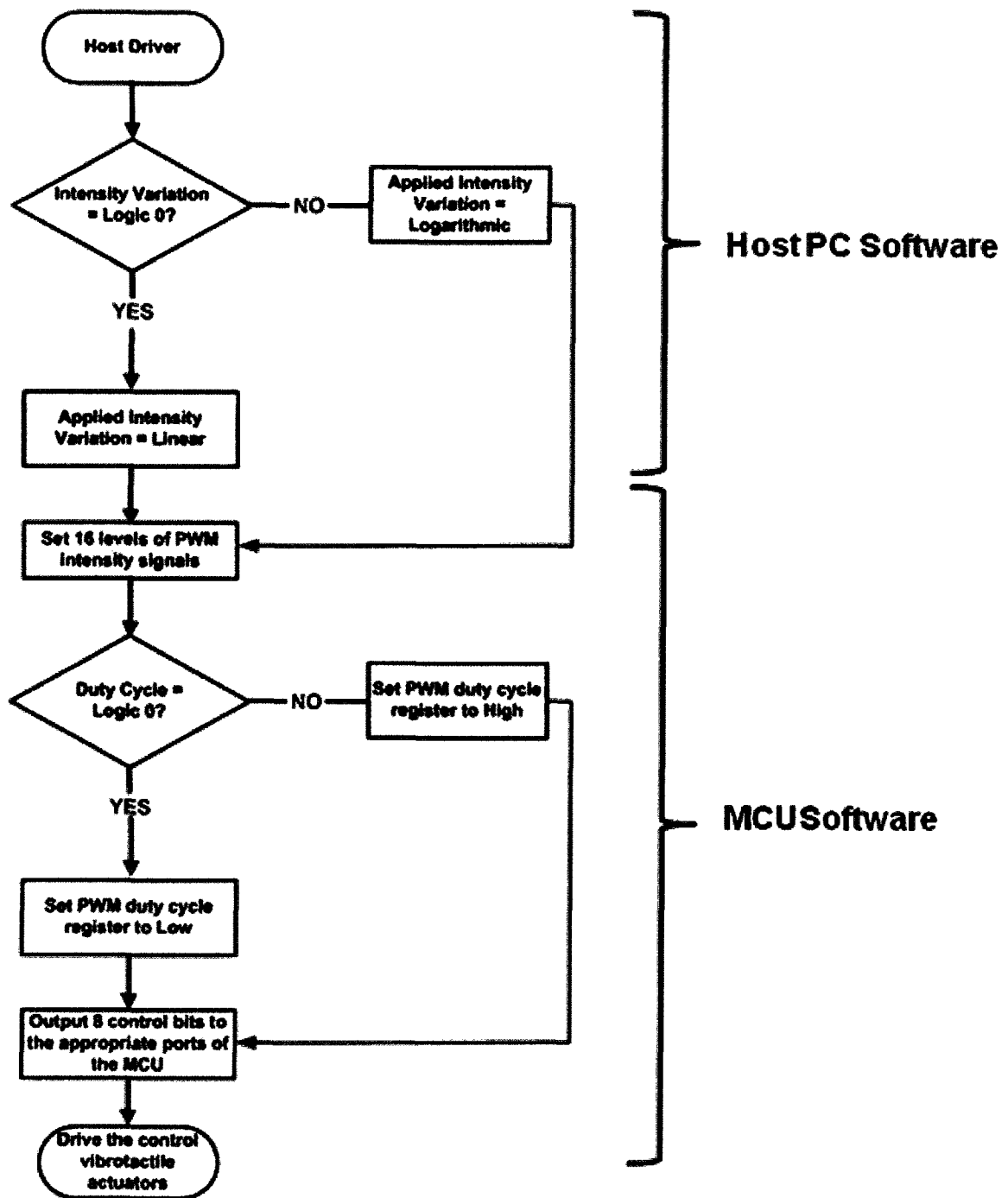


Figure 4.1: Control Software Architecture

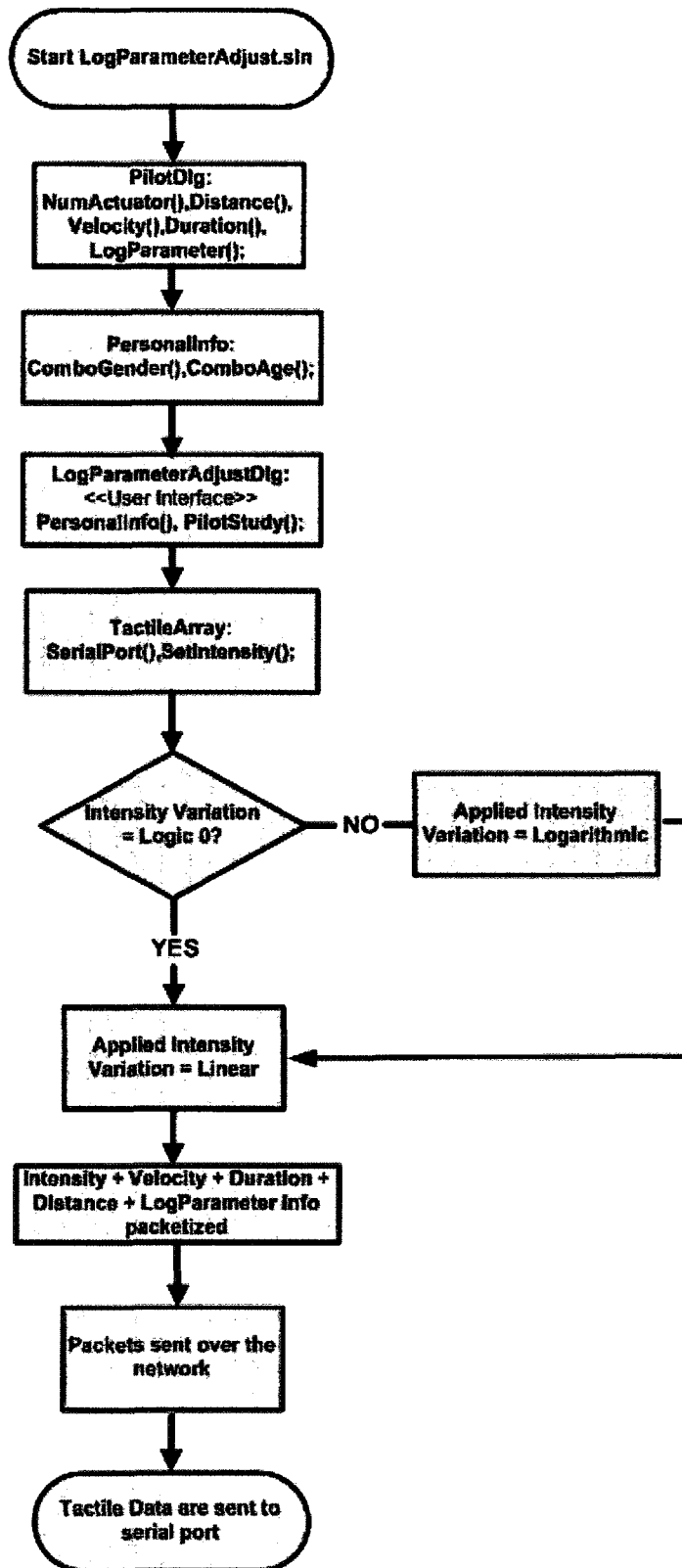


Figure 4.2: Host Driver Architecture

### 4.2.3 Continuous Movement Algorithm

The continuous movement algorithm is implemented in the Tactile Array class to deliver a linear or logarithmic intensity variation to the vibrotactile actuators. The algorithm is implemented as the equations (3.1) and (3.2) in Section 3.1 as shown in Figure 4.3.

The continuous movement algorithm controls the intensities of the adjacent actuators with inverse proportional intensities. For the linear intensity variation, the magnitude of Actuator A decreases linearly from the maximum applied intensity level to the minimum applied intensity level. The magnitude of Actuator B increases linearly from the minimum applied intensity level to the maximum applied intensity level for a given time interval. Similarly, for the logarithmic intensity variation, the magnitude of Actuator A decreases logarithmically from the maximum applied intensity level to the minimum applied intensity level. Subsequently, Actuator B increases logarithmically from the minimum applied intensity level to the maximum applied intensity level over a given time interval. The intensity variations are then mapped to the serial interface and then delivered onto the MCU to the vibrotactile actuators.

```

for(i=0; i<m_nNumActuators-1; i++) {
  for(j=0; j<MAX_APPLIED_INTENSITY; j++) {
    switch(m_nMode) {
      case 0://Linear intensity variation
        MagA = MAX_APPLIED_INTENSITY-j; //Linear intensity Variation for Actuator A
        MagB = j; //Linear intensity variation for Actuator B
        break;
      case 1://Log intensity variation
        MagA = (int)floor( log(1.0+m_fLogParameter*(MAX_APPLIED_INTENSITY-j)/MAX_APPLIED_INTENSITY) /
          log(1.0+m_fLogParameter) * MAX_APPLIED_INTENSITY +0.5f); //Log intensity for Actuator A
        MagB = (int)floor( log(1.0+m_fLogParameter*j/MAX_APPLIED_INTENSITY) /log(1.0+m_fLogParameter) *
          MAX_APPLIED_INTENSITY +0.5f); //Log intensity for Actuator B
        break;
    }
  }
}

```

Figure 4.3: Continuous Movement Algorithm

## 4.3 Hardware Architecture

The following subsections discuss the hardware implementation design of the vibrotactile system.

### 4.3.1 Circuit Diagram

As a prototype, the vibrotactile system contains multiple vibrotactile actuators located on the dorsal forearm and upper arm of the wearer that simulate a continuous movement sensation. The vibrotactile circuit diagram shown in Figure 4 shows the electrical connections between the components in Table 4.1.

Table 4.1: **Vibrotactile Circuit Components**

Diagram Label	Circuit Component
VCC 9V	Power supply
POWER SWITCH	Power switch
MCU AVR	ATmega128
Serial Port Connector	RS-232 module from Schmart-Board.Inc
LM7805	5V Voltage regulator (LM7805)
Actuator	Vibrotactile actuators
LED	LED for Power Indication

Shown in Figure 4.4, the vibrotactile circuit diagram simulated in National Instrument Multisim software is illustrated as follows:

First, a 9 volt battery power supply integrated with a power switch is used to power the vibrotactile system. The power switch includes a LED with a 1 kOhms resistor to limit the current from the LED, and provide indication that the power supply is ON or OFF.

The ATmega128 microcontroller has an operating voltage between 4.5-5.5V and a 5V voltage regulator (LM7805), and was added into the circuit to drive the MCU to control the electronic components, such as the serial port connector and the vibrotactile actuators.

The serial port Rx is connected to MCU Rx pin 2 (PE0) and the serial port Tx is connected to MCU Tx pin 3 (PE1) to drive the circuit for the appropriate I/O ports PORTA (pins A0/51.....A7/44). The ATmega128 MCU has a maximum current of 200mA and the vibrotactile actuators require 110mA which is suitable for driving the vibrotactile actuators.

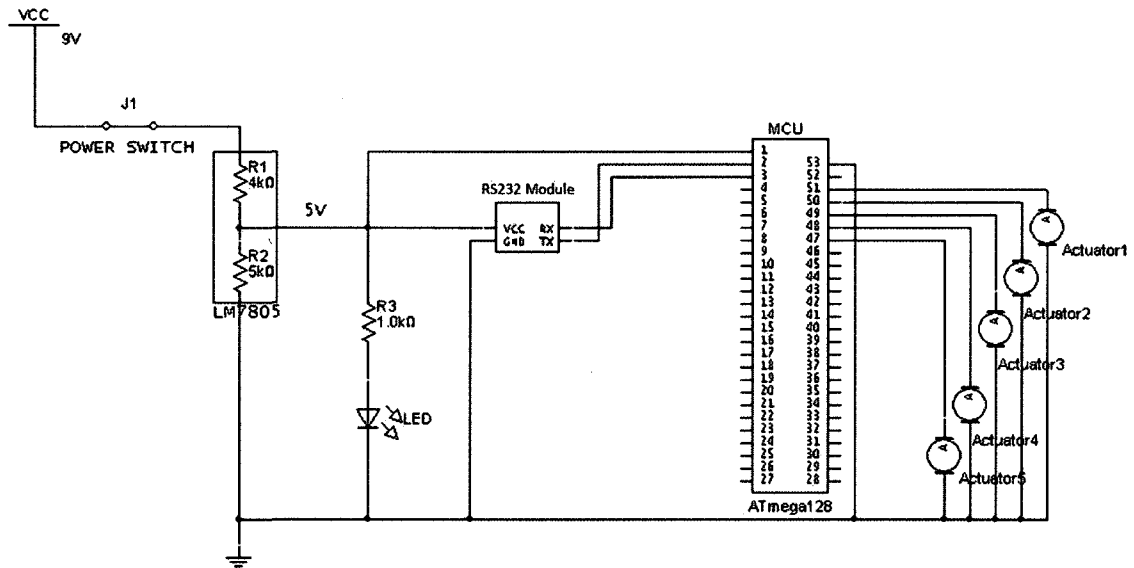


Figure 4.4: Vibrotactile Circuit Diagram

### 4.3.2 Controlling Algorithm

The controlling algorithm programmed in C using WINAVR, has been developed for the ATmega128 microcontroller to control the activation of the actuators based on commands received from the host driver. The PWM algorithm is summarized in Figure 5. The algorithm first initializes the serial UART0 com port and makes the MCU enter a logic loop waiting for two characters to appear on its serial Rx pin 2 (PE0). Upon the reception of the two characters, 16 levels of PWM binary signals are sent to the I/O ports PORTA (pins A0....A7) to control the vibrations of the vibrotactile actuators as described in Section 3.2.2

```

unsigned short PWM[NUM_INTENSITY][NUM_PWM] = { {0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0},
{1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0},
{1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0},
{1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0},
{1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0},
{1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0},
{1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0},
{1,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0},
{1,1,1,1,1,1,1,1,1,1,1,1,0,0,0,0},
{1,1,1,1,1,1,1,1,1,1,1,1,1,0,0,0},
{1,1,1,1,1,1,1,1,1,1,1,1,1,1,0,0},
{1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,0},
{1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1}
};

```

Figure 4.5: Controlling Algorithm

In this chapter, the models introduced were used to design the software and hardware architecture of our vibrotactile system. These models include the control software architecture, host driver architecture, continuous movement algorithm, circuit diagram and controlling algorithm. The integration of these components allowed us to simulate and conduct our experimental results, which are discussed in the following chapter.

# Chapter 5

## Evaluation and Results

Four psychophysical experiments are conducted to measure users' judgments about the quality of the continuous movement created with a low-resolution dynamic vibrotactile display. We evaluate the optimum control conditions which are the temporal order, spatial sensitivity and amplitude variation of the continuous movement to prove the feasibility of our proposed approach. The psychophysical experiments are approved by the University of Ottawa ethics committee and all subjects participated signed informed consent forms see Appendices( A.2 and A.3). Each experiment is conducted approximately seven weeks apart. The psychophysical experiments and measurements are described in detail in the following sections.

### 5.1 Psychophysical Experiment I- Piolt Study

A pilot study was conducted prior to the main research to check the feasibility of the continuous touch sensation using a dynamic vibrotactile device on the human's dorsal forearm, applying the funnelling illusion. The funnelling illusion is used to present a continuous touch sensation by changing the applied intensities of two adjacent vibrotactile actuators linearly on the skin. The continuous sensation is dependent on three control conditions: separation of the stimuli, relative amplitudes and temporal order.

Two experimental settings took place; each lasted for approximately 35 minutes. The first experiment measured perceived intensities - the relationship between the applied intensities and the perceived intensities of the subjects. The second experiment investigated the optimal range of distance between the two stimuli and the temporal order of the funnelled location for producing a continuous sensation along the forearm.[18]

### 5.1.1 Goal

The goal of the pilot study was to determine the perceived intensities by the subjects and the perceptual parameters or control conditions for creating a continuous touch sensation on the dorsal forearm.

### 5.1.2 Perceived Intensity

#### Methodology

For the first experiment, human perceived intensity was measured as a control parameter for producing continuous movement. The perceived intensities are the subjects' judgments of the vibrotactile actuator intensities applied on the skin. As described in Chapter 3, the intensities of the vibrotactile actuators are controlled by PWM, which affects the frequency of the applied actuators, which in return varies the magnitude of the vibration being produced. Therefore, the perceived intensities are measured with respect to the applied intensities based on the duration of the PWM signal.

Seven subjects from the University of Ottawa community participated, consisting of 3 males and 4 females, ranging in age from 23 to 29 years. The right forearm was tested and all but one of the subjects were left handed. None of the subjects reported any sensory difficulties. The applied intensities of the vibrotactile actuators have 15 levels, as described in Chapter 3; however, only half of the applied intensities are used for the experiments, allowing the subjects to differentiate the applied intensities more accurately. The levels of intensities applied were: 2, 4, 6, 8, 10, 12 and 14.

The vibrotactile device was placed on the subjects' dorsal forearm while one vibrotactile actuator was comfortably placed in the center of the forearm, between the wrist and elbow, using the arm band strap. The following dimensions of the forearm of each subject were measured with a measuring tape: the circumference of the wrist, the circumference of the elbow and the length of the forearm. This ensured accurate central placement of the vibrotactile actuator for each subject, shown in Figure 5.1[38].

Actuator placements were tangential to the skin's surface, creating a better distinct sensation than stimulators normal to the surface of the skin, based on Alles 1970 and Bekesy 1958.

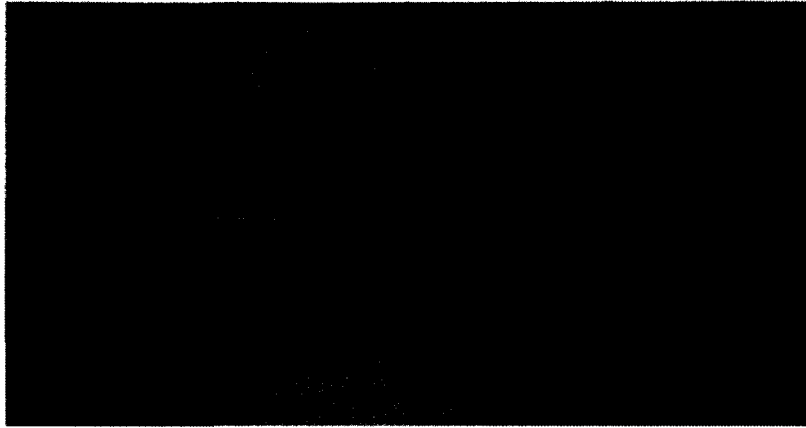


Figure 5.1: Vibrotactile central placement on the forearm

Subjects were told that the experiment would test their ability to discriminate between various applied intensities. Experimental instructions were provided to the subjects to help them understand the experiment's procedures. To verify that the subjects were unable to hear auditory cues from the vibrating actuators, which may affect judgment of perceived intensity, the subjects wore headphones that played white noise.

For the first session (the training session), subjects were trained with the 7 levels of the applied intensities. The vibrating stimulus was applied and presented on the subjects for 2 seconds followed by a 1 second break. This session was repeated until the subjects felt comfortable in their ability to reproduce the applied intensities.

In the second session, a randomly order of the 7 applied intensities were presented and the subjects were asked to judge the applied intensities. Each stimulus of the vibration was presented 5 times; as a result, 35 stimuli were presented to each subject.

### 5.1.3 Results

To analyze the data, subjects' responses of perceived intensities had to be normalized to accommodate for differences in scaling judged from each subject. Later, each perceived intensity was averaged across all the subjects. The lowest average perceived intensity was determined as 2 and the highest average perceived intensity was 14.

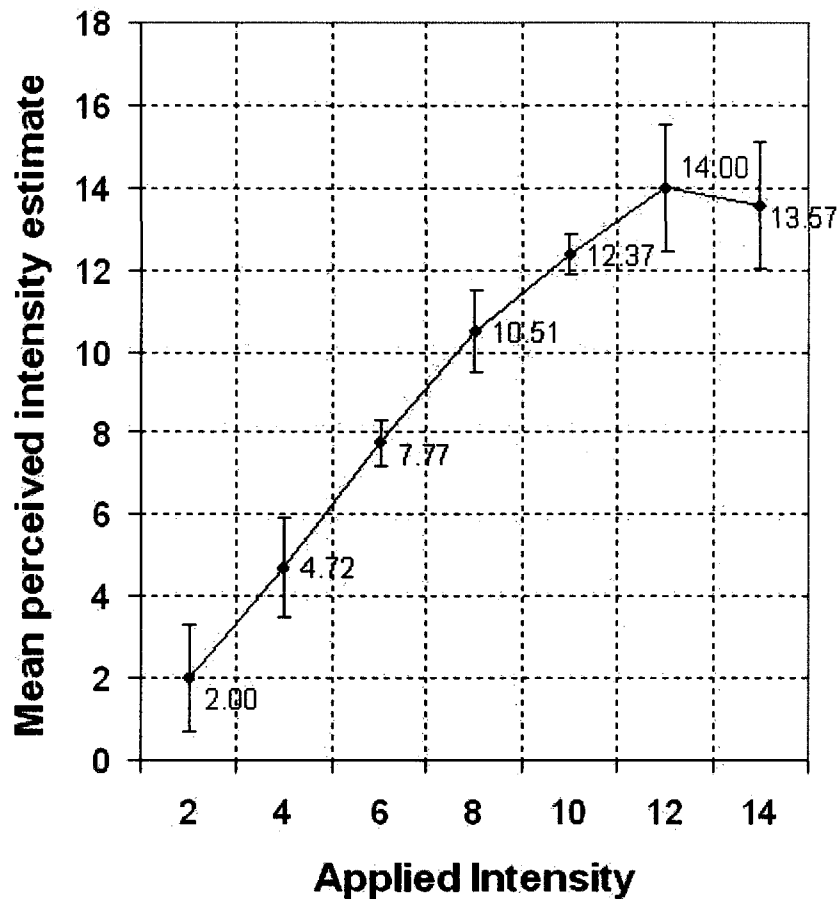


Figure 5.2: Relationship between the level of perceived intensity as a function of the applied intensity[18]

Figure 5.2 shows an approximate proportional relationship between the average responses of perceived intensities with standard errors as a function of the applied intensities. The perceived intensities show monotonic increases until level 12 of applied intensity. Thus, for anything greater than applied intensity 12 and less than applied intensity 2, subjects could not differentiate applied intensities. To measure the correlation relationship between the applied intensities and perceived intensities, a linear fit to the applied intensities and corresponding perceived intensities reveals a slope of 1.224 and a y intercept of -0.008, with a Pearson's correlation coefficient of 0.99; a magnitude near 1 represents a good fit between the two intensities.

The linear fit shown in Table 5.1 represents the relationship between the perceived intensities and applied intensities. In order to produce the continuous feeling for experiment II, we changed the applied intensities to the users' corresponding perceived intensities, limiting the applied intensities to the range of control values between zero and twelve in order to ensure linear tactile excitement when activating the vibrotactile actuators.

**Table 5.1: Applied intensities corresponding to the perceived intensities based on the linear fit**

Perceived Intensity	Applied Intensity	Applied Intensity Rounded Off
1	0.823	1
2	1.640	2
3	2.457	2
4	3.274	3
5	4.091	4
6	4.908	5
7	5.725	6
8	6.542	7
9	7.359	7
10	8.175	8
11	8.992	9
12	9.809	10
13	10.626	11
14	12	12

## 5.1.4 Control Conditions

### Methodology

The second experiment was to prove the feasibility of creating a continuous touch sensation by determining two control conditions: the distance between the two vibrotactile actuators and the velocity of the funnelling illusion movement. As explained in Chapter 3, the funnelling illusion causes subjects to feel one sensation from two separate adjacent stimuli on the skin. Thus, in this experiment, we also confirm if subjects can feel a continuous touch sensation and not two separate stimuli. After measuring the dimensions of each subject's forearm, as described earlier in Section 5.1.2, two vibrotactile actuators were placed in the center of the forearm, separated by specific distances; one vibrotactile actuator was located towards the wrist and the other towards the elbow, using arm band straps.

Each set of stimuli was presented by varying the distances between the two actuators from 20mm, 40mm, 60mm, 80mm, 100mm, and by varying the velocity from 5mm/s, 10mm/s, 20mm/s, 40mm/s, 60mm/s, 80mm/s, 100mm/s, 200mm/s, 500mm/s. The subjects were asked to rate the quality of the continuous movement; high quality for continuous sensation was based on four criteria:

1. Subjects should feel one location of the stimulus
2. The location of the funnelled stimulus should move smoothly
3. The stimulus should be running at the same intensity levels
4. The stimulus should be moving straight without any discreteness

However, if the funnelling illusion failed - that is, if subjects were unable to sense any movement or felt two separate stimuli - the score was recorded as zero.[18]

## 5.1.5 Results

To analyze the data, subjects' responses of perceived intensities were adjusted to accommodate for differences in scaling judged by each subject. Subjects' responses to the quality of the continuous sensation were normalized from 0 to 10.

Table 5.2 shows the two control conditions that represent the average responses about the quality of the continuous sensation as a function of the stimulus velocity and distance.

Table 5.2: Normalized subjective scores for continuously moving sensation as a function of the distance between two actuators and velocity of the movement. The standard deviations are shown in the parenthesis.

Velocity (mm/sec)	Distance(mm)				
	20mm	40mm	60mm	80mm	100mm
5 mm/sec	3.0(3.2)	1.5(1.3)	2.5(1.8)	2.0(1.9)	1.1(0.9)
10 mm/sec	4.0(3.1)	4.8(3.2)	3.6(3.4)	2.7(3.0)	4.7(1.5)
20 mm/sec	6.5(2.6)	6.1(3.1)	7.0(3.1)	6.4(3.1)	5.2(2.6)
40 mm/sec	6.2(2.4)	7.0(1.2)	7.0(1.8)	7.0(2.8)	4.7(2.5)
60 mm/sec	5.5(2.4)	7.0(1.8)	7.5(1.7)	7.4(2.0)	4.9(3.2)
80 mm/sec	5.5(1.8)	7.2(0.8)	7.5(1.2)	7.5(2.5)	4.9(2.3)
100 mm/sec	4.6(3.9)	5.7(1.2)	5.7(2.5)	6.6(2.3)	5.2(3.1)
200 mm/sec	4.0(3.6)	2.8(3.7)	6.8(1.8)	6.1(1.6)	5.4(2.9)
500 mm/sec	4.1(3.6)	2.9(3.8)	2.5(3.8)	2.4(3.9)	2.3(3.7)

An illustration of Table 5.2 is also presented on a 2-dimensional graph, shown below in Figure 5.3.

As the graph illustrates in Figure 5.3, the quality of the continuous movement is well presented in the vicinity of 60mm distance and 60mm/s velocity. The quality of the continuous movement decreased as the velocity increased to greater than 200mm/s and decreased to less than 10mm/s. The faster the velocity, the more subjects reported to have felt two distinct stimuli. The slower the velocity, the dimmer the movement was perceived, or the movement felt disconnected midway. As regards to the distance, at 20mm, subjects were unable to distinguish movement accurately. However, when distance exceeded 80mm, users felt that the perceived intensity of the funnelled stimulus was becoming very faint.

Proven by Alles, if the applied intensity of each actuator changes linearly, the funnelled sensation will be perceived to decrease towards the center of the two stimuli. In order to produce funnelled movement of constant intensity, the perceived intensity needs to be adjusted logarithmically[9]. However, subjects reported that they did not feel this decrease in intensity in the region of higher quality shown in Figure 5.3. Thus, from Figure 5.3, a range of distance from 40mm to 80mm between the two stimuli on the dorsal forearm produces continuous sensation.

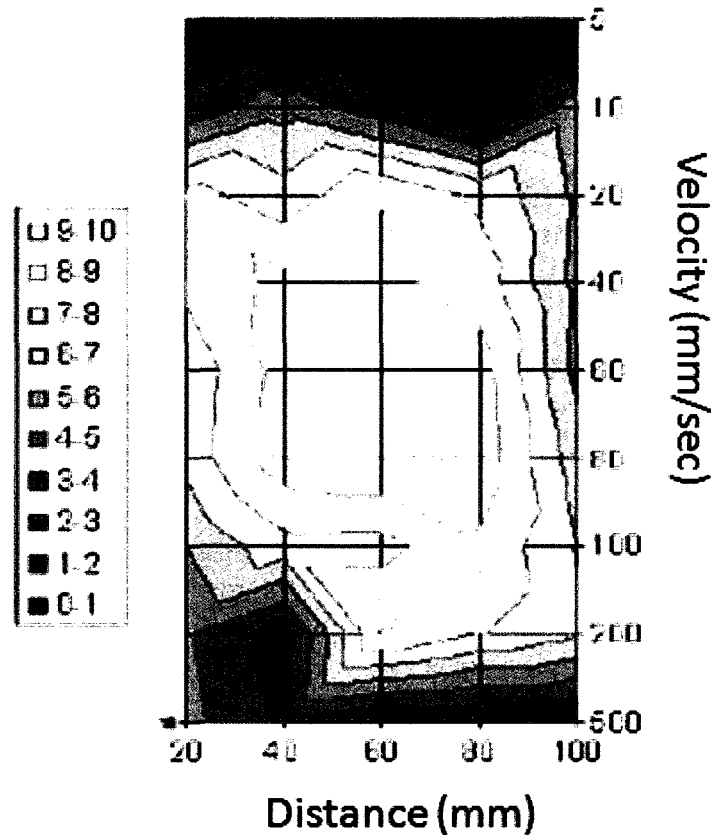


Figure 5.3: The average subjective scores for continuously moving sensation. The lighter area represents more apparent and continuous movement along the forearm.[18]

### 5.1.6 Discussion

For the pilot study test, we performed two psychophysical experiments to demonstrate the feasibility of using funnelling illusion to simulate continuous touch feeling on the dorsal forearm. The first experiment determined the human perception intensity as the relationship between the applied intensities and the perceived intensities. The second experiment focused on the feasibility of simulating continuously moving touch by determining two control conditions: the distance between the two vibrating motors and the velocity of the funnelled stimulus location. As a result, continuously moving touch sensation was apparently perceived in the vicinity of 60mm distance and 60mm/s velocity. We believe the proposed control methods will increase the readability of information presented by vibrotactile devices. We further investigate the feasibility of the quality

of continuous vibrotactile sensation by determining if the applied intensities need to be adjusted logarithmically to produce a continuous movement of constant intensity, as proposed by Alles in 1970.

## 5.2 Psychophysical Experiment II- Feasibility Test

The feasibility test investigates the temporal intensity changes of two low-resolution vibrotactile actuators in a linear and logarithmic intensity variation to produce continuous movement.

### 5.2.1 Goal

The goal of the feasibility test is to investigate three control conditions that are dependent on the quality of continuous movement: 1) the amplitude variation, which is the intensity change of the vibrotactile actuators in a linear and logarithmic pattern; 2) the distance of the continuous movement, which is the separation of the two stimuli; 3) the orientation of the continuous stimulus. Psychophysical experiments revealed an interesting relationship between the distance and orientation of the two vibrotactile actuators with the preferred intensity variation.[39]

### 5.2.2 Methodology

Fourteen subjects from the University of Ottawa community participated, consisting of 6 males and 8 females, ranging in age from 23 to 29 years. The right forearm was tested and all but one of the subjects were left handed. None of the subjects reported any sensory difficulties.

Subjects were provided with experimental instructions to help them understand the experiment's procedures. For the experimental setup, two sessions took place, each lasting approximately 35 minutes. First, a training session was prepared to familiarize the subjects with the influence of linear and logarithmic intensity variation along the transverse and longitudinal direction on the forearm. The dimensions of each subjects' forearm were measured as in Section 5.1.2, ensuring central placement of the actuators.[39]

An illustration of the applied linear and logarithmic intensity variation is shown in Figure 5.4. As described in Section 3.1, the continuous movement formulas are applied

by varying the intensities of adjacent tactile stimuli with inverse proportional intensities. The level of applied intensity labeled '0' means the actuator is off and the maximum intensity level labeled '12' is set as the maximum applied intensity the actuators can produce at 3.6 volts.

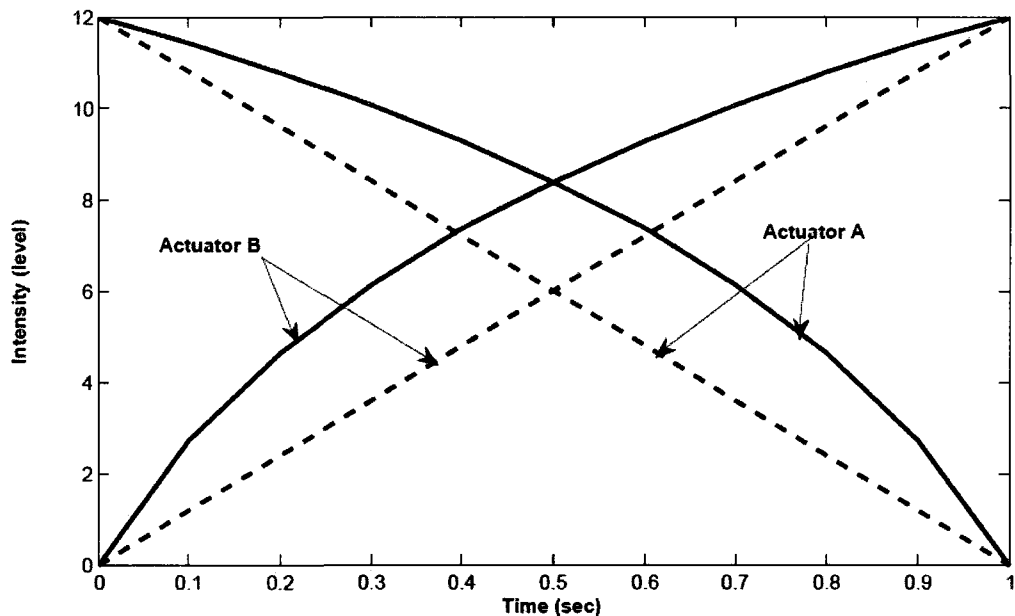


Figure 5.4: Applied Linear and Logarithmic Intensity Variation

For a linear variation, the dash line represents the intensity of one vibrotactile actuator B increasing linearly from level 0 to 12 levels for a 1 second time interval, and the second vibrotactile actuator A intensity decreases linearly from 12 to 0 levels for a 1 second time interval, staying within the preferred dynamic range of the perceived intensity as proposed in section 5.1.2. The same approach was done for the logarithmic variation, where the sold line represents the intensities of two vibrating actuators changing with inverse proportional intensities logarithmically within the same dynamic range. During the training session, the linear and logarithmic intensities were applied on the subjects' forearm until the participants were able to distinguish between the linear and logarithmic intensities. The logarithmic functions were selected based on subjects' preferences, which they described as a reasonable continuous one tactile stimulus movement. After distinguishing between the linear and logarithmic intensities, subjects reported the log-

arithmetic intensity to have a stronger intensity output compared to the linear intensity which reflects Alles' work[9].

The screenshot shows a window titled "ParameterAdjust". It contains the following elements:

- Subject Name:** A text input field with the value "A. B. C."
- Velocity:** A dropdown menu showing "70" and a "Stop Test" button to its right.
- Distance:** A label "Distance: 70" above a large empty rectangular area.
- Activate:** A button located at the bottom of the large empty area.
- Choose your favorite settings:** A section with two radio buttons: "Setting A" (selected) and "Setting B".
- Submit:** A button at the bottom of the interface.

Figure 5.5: User Interface for Experiment II

After training the evaluation session began, as in the pilot study the subjects wore headphones playing white noise to ensure they were unable to hear auditory cues from the vibrating motors. A user interface implemented using Microsoft Visual Studio 2005 was displayed for the participants shown in Figure 5.5. Five trials of randomly ordered linear and log intensity stimulus were presented and the subjects selected the preferred intensity variation from two settings on the user interface. Subjects were asked to judge the applied intensities based on a continuous movement of one tactile stimulus without perceiving two separated stimuli related to the four criteria in Section 5.1.4. Each stimulus was presented 5 times with 5 random distances.

As a result, 25 stimuli were presented to each subject along the longitudinal and transverse orientation.

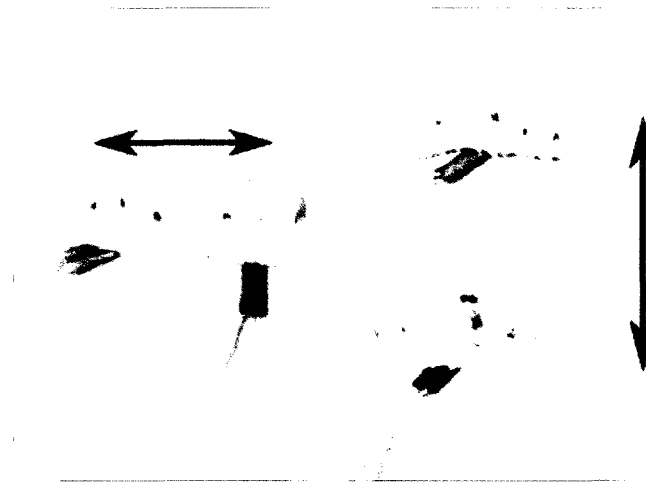


Figure 5.6: Distances and orientations of the vibrotactile actuators are changed randomly for experiments to investigate the optimum continuous sensation

The continuous movement was examined as the armbands straps were wrapped around the subject's dorsal forearm along the transverse and longitudinal direction. Illustrated in Figure 5.6, for the transverse direction, two actuators were placed on one armband strap. For the longitudinal direction, each actuator was placed on a separate armband strap. For each orientation, 5 distances were varied in a random order. The distances of the actuators were changed from 30mm, 40mm, 50mm, 60mm and 70 mm, as a continuous movement sensation within this range is to be expected based on the pilot study test. For each configuration, two tests were applied on the subjects forearm referring to the linear and logarithmic variation.[39]

### 5.2.3 Results

Based on the subjective answers of our 14 test subjects, Figure 5.7 and Figure 5.8 shows the amount of preferences of the two offered intensity variations for each distance along the transverse and longitudinal direction. The black bars represent preferable linear intensity change, while the grey bars display the amount of preferences for the logarithmic intensity change.

Matlab(Version.7.4.0., 2007) was used to read and combine all data from the participants; the summary of our results are shown in Figure 5.7 and Figure 5.8.

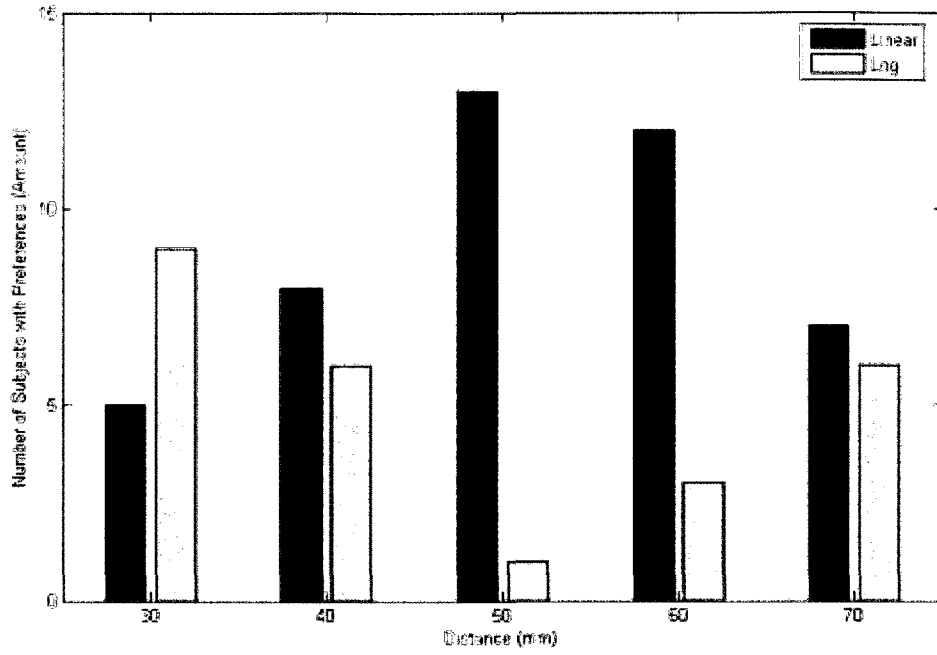


Figure 5.7: Average results for the longitudinal orientation for each distance[39]

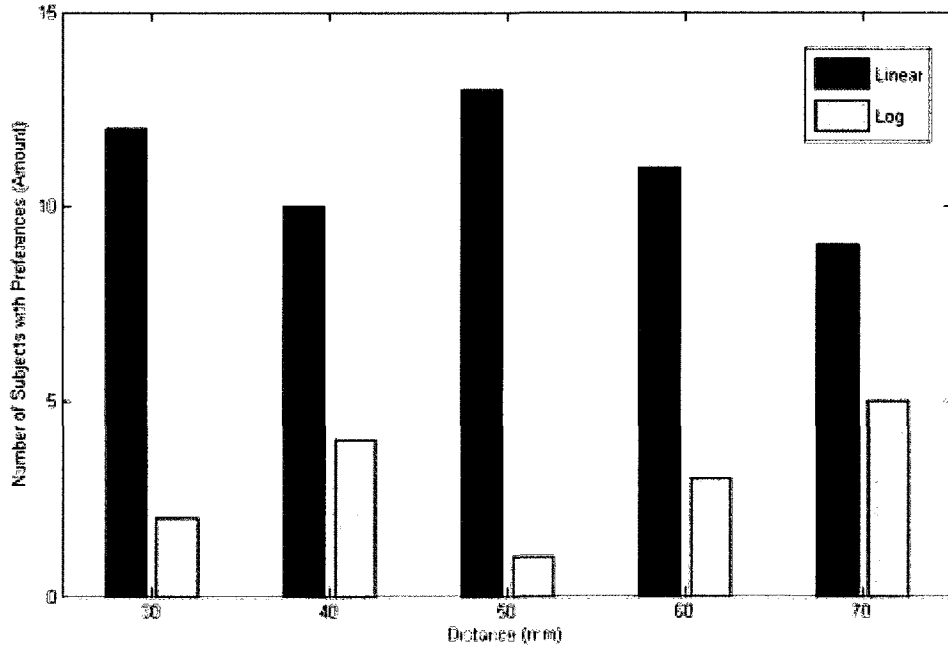


Figure 5.8: Average results for the transverse orientation for each distance[39]

Figure 5.7 shows our results for the longitudinal direction. For the distance of 50 mm, the linear intensity change was clearly favoured. According to the pilot study, this distance range is also preferable for displaying a continuous movement sensation. As we increase or decrease the distance from 50 mm, the amount of linear preferences decreases. Accordingly, at 50 mm, the logarithmic intensity variation was least preferred; as we increase or decrease the distance, it became more preferable. By looking at the ratio of the linear and logarithmic preferences for each distance, we see an interesting Gaussian like behaviour.

Interestingly, this result reflects Cholewiak et al.'s[19] work on spatial sensitivity, which proved that the increase of vibrator separation from 25mm to 50mm on the forearm increased recognition accuracy from 46% to 66%; see Section 2.1.1.

Figure 5.8 illustrates the results for the transverse direction. In this case, the linear intensity variation is strongly favoured for all distances. Similarly, for longitudinal direction, a 50mm distance is shown as the preferred distance for displaying continuous movement. The favouring of linear intensity variation for all distances could be due to a different propagation of vibration on the human skin along longitudinal and transverse directions. Subjects reported a more clear and constant uniform intensity of the continuous movement for the transverse orientation since only a single armband strap was used around the dorsal forearm. Thus, for the transverse orientation, the use of a single strap might produce clearer intense vibratory stimuli that are transmitted from one vibrator to the other.

This observation reflects findings that were significantly proven by authors Cody et al, who reported tactile spatial perception was greater in the transverse than longitudinal axis along the upper limb (i.e.: forearm and hand)[22]. Oppositely, physiologist E.H Weber's classical work on the tactile senses reported that humans can distinguish touch easily when two simultaneous stimuli are presented longitudinally rather than transversely, due to the longitudinal orientation of the many nerve endings along the arms[40]. We will further investigate the preferable orientation for continuous movement along the upper limb.

### 5.2.4 Discussion

For the feasibility test, we investigated critical parameters of the psychophysical continuous movement sensation. The influence on the temporal variation of intensity changes in a logarithmic and linear pattern between two vibrotactile actuators are evaluated, according to the distances and orientations. Our results show an interesting behaviour, as we obtained a favoured linear intensity variation for the longitudinal orientation at a distance of 50mm. However, for smaller or larger distances, the logarithmic intensity variation becomes preferable. Surprisingly, for the transverse orientation, the linear intensity variation was favoured for all distances, but the preferred distance was also 50mm. Although 50mm had the highest mean for displaying continuous movement, 50 mm is taken to be the favourable interstimulus distance.

To investigate the background of our results, further psychophysical experiments are conducted on the control parameters to obtain optimum continuous movement. Additionally, we further investigate a logarithmic function to provide the best possible continuous movement presentation.

## 5.3 Psychophysical Experiment III-Optimum Control Conditions

Experiment III determines the optimum control conditions for displaying continuous movement. We increase the number of vibrotactile actuators to four, obtaining better judgment quality of continuous movement from the subjects while maintaining minimum hardware. Repeated measures of variance analyses (ANOVA) were performed to prove the statistical significance of our results. As well SPSS 17 (SPSS Inc, Chicago, IL, USA) a predictive analytic software was used to perform the Post Hoc test using Tukey's multiple comparison test to determine which control conditions were significantly different from one another.

### 5.3.1 Goal

The goal for Experiment III is to test our hypothesis that the quality of continuous movement will be significantly different for the following control conditions: 1) Intensity variation, which is the intensity change of the vibrotactile actuators in a linear and logarithmic pattern; 2) Limb axis which is the transverse and longitudinal orientation of

the continuous movement; 3) Limb site which is the location of the continuous movement along the forearm and upper arm; 4) Gender which is the differences between males and females and 5) Duration of the stimulus (DOS) which is the temporal order of the continuous movement.

### 5.3.2 Methodology

Twelve subjects from the University of Ottawa community participated, consisting of 7 males and 5 females, ranging in age from 23 to 29 years. The right forearm and upper arm were tested and all but one of the subjects were left handed. None of the subjects reported any sensory difficulties. The same experimental set up as Experiment II was performed and the test lasted approximately 45 minutes.

The dimensions of each subject's forearm and upper arm were measured to ensure central placement of the actuators. Figure 5.9 shows the placement of the four actuators on the dorsal forearm, separated by an inter-stimulus distance of 50mm; this distance is within the range for displaying the best possible continuous movement based on Experiments I and II. The same configuration was made for the upper arm.

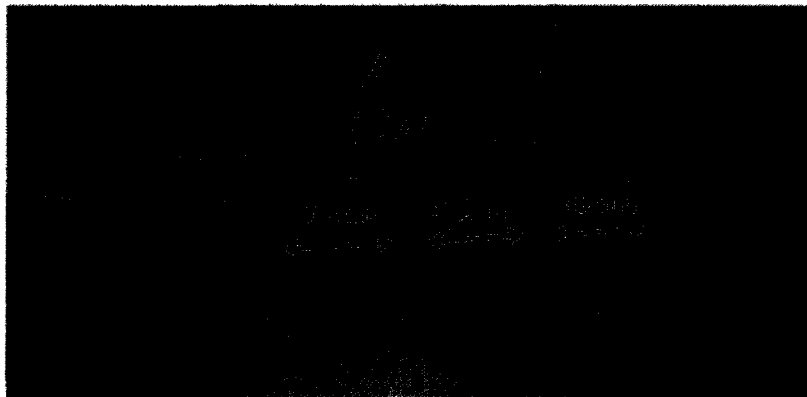


Figure 5.9: Illustration of the interstimulus distance of the four vibrotactile actuators on the dorsal forearm for Experiment III

As in Experiment II, a training session was prepared to help the subjects become familiar with the difference between linear and logarithmic intensity variation along the transverse and longitudinal direction on the forearm and upper arm. Once the participants became familiar with the two intensity variations, the evaluation session began. Subjects wore

headphones that played white noise in order to avoid hearing auditory cues from the vibrotactile actuators.

The linear and logarithmic intensities were applied three times on the subject's forearm at eleven different stimulus durations, between 100msec to 1000 msec. In total, 66 stimuli were presented to the subjects dorsal forearm and upper arm along the transverse and longitudinal directions.

The order of the evaluation session is summarized in the steps bellow:

1. Random order of linear and logarithmic intensities were applied on the subjects forearm
2. Each stimulus was applied three times for the transverse direction on the forearm
3. Steps 1-2 were applied for stimulus durations (DOS) at (100, 110, 130, 150, 200, 240, 360,480, 600, 960, 1000) msec
4. Subjects judged the quality of the continuous movement from 0 to 100%, where 100% was rated as a high quality of the continuous movement based on the four criteria in Section 5.1.4
5. Steps 1-4 was repeated for the longitudinal direction on the forearm
6. Steps 1-5 was repeated for the upper arm

### **5.3.3 Results**

Subjects' responses to the quality of the continuous movement were normalized to accommodate differences in scaling from each subject. This is done by normalizing each subject's mean of 66 trials followed by multiplying with the grand mean for all subjects. The normalized responses were examined by ANOVA for each control condition. Five statistical tests were examined by ANOVA for each control condition and ANOVA indicated that only two of the control conditions - the intensity variations and DOS - had a significant effect on the quality of the continuous movement.

Five statistical tests were examined for the control conditions, and the hypothesis for each main effect is described in Table 5.3:

Table 5.3: Hypothesis for Main Effects

Main Effect for Limb Axis	Main Effect for Limb Site	Main Effect for Gender	Main Effect for Intensity	Main Effect for DOS
$H_0: \mu_{Trans} = \mu_{Long}$	$H_0: \mu_{Forearm} = \mu_{Upperarm}$	$H_0: \mu_{Male} = \mu_{Female}$	$H_0: \mu_{Linear} = \mu_{Log}$	$H_0: \mu_{DOSa} = \mu_{DOSb}$
$H_a: \mu_{Trans} \neq \mu_{Long}$	$H_a: \mu_{Forearm} \neq \mu_{Upperarm}$	$H_a: \mu_{Male} \neq \mu_{Female}$	$H_a: \mu_{Linear} \neq \mu_{Log}$	$H_a: \mu_{DOSa} \neq \mu_{DOSb}$

We reject the null hypothesis  $H_0$ , if the sample means are equal. Otherwise we accept,  $H_a$  if the sample means are different at a certain significance level  $p$ .

$\mu$  = represents the mean of the control conditions

$p = .05, .01, .0001$  represents the significance level

### 1. Main Effect for Intensity Variations

Based on the subjective answers of our 12 test subjects, figure 5.10 shows linear intensity has a mean of 50% and the logarithmic intensity has a mean of 40% towards the quality of the continuous movement. As a result, subjects favour the linear intensity variation for displaying the best possible continuous movement. This result contradicts Alles's[9] proposed work, which made the theoretical point that linear variation decreases the funnelling illusion at the midpoint between the two stimulators. Based on the 12 subjective judgments, linear intensity is clearly favoured for displaying a high quality of the continuous movement. This observation is supported by the results of ANOVA, where the mean for the linear intensity variation is significantly different from the mean of the logarithmic intensity variation, where  $F(1,1055)=24.28$ , ( $p < 0.0001$ ). As well, the same result is shown in the T-test,  $t(1054)=4.92$ , ( $p < 0.0001$ ), thus intensity variations are significantly different on the quality of the continuous movement.

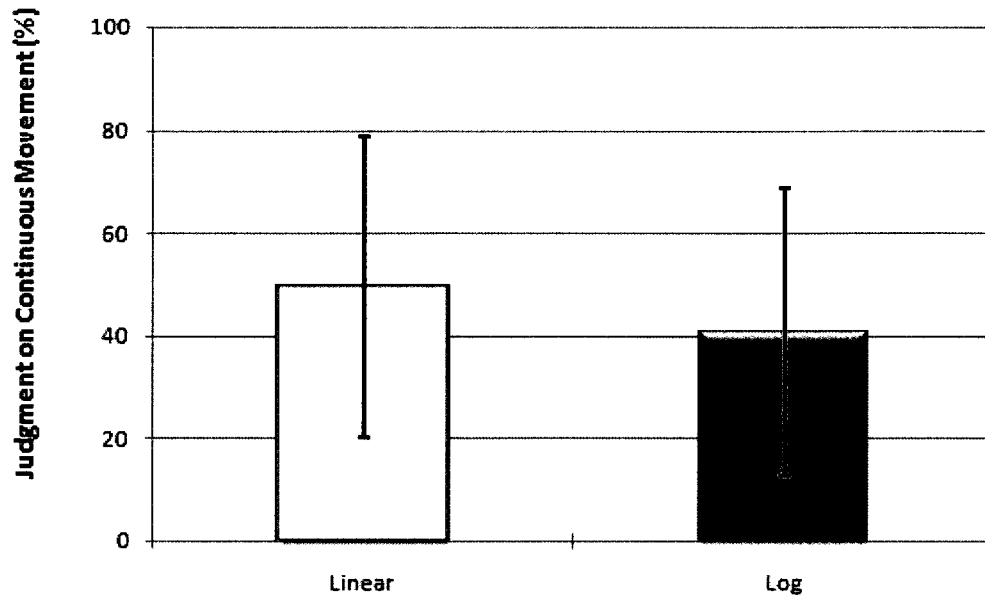


Figure 5.10: Mean judgments in percentage as a function of the intensity variations with standard deviation

## 2. Main Effect for Limb Axis

Figure 5.11, shows linear intensity is favoured at the longitudinal and transverse orientations based on subjects' judgments on the quality of the continuous movement. Observed by ANOVA, the longitudinal and transverse orientations were found to have no main effect on the quality of the continuous movement, where  $F(1, 1055)=0.07$ ,  $p=0.78$ . Additionally the T-test reveals no significant difference between the orientations,  $t(1054)=1.96$ ,  $p=0.78$ . Two-Way ANOVA, however shows a significant interaction effect between the orientations and intensity variations on the quality of the continuous movement -  $F(1,1055)=4.7$ , ( $p < 0.05$ ).

For the transverse orientation, no significant difference was shown in the T-test,  $t(1054)=1.96$ ,  $p=0.0525$  with respect to the intensity variations. However a significant difference was seen in the T-test for the longitudinal orientation,  $t(1054)=1.96$ , ( $p < 0.0001$ ) with respect to the intensity variations. This result can be seen in figure 5.11, where the linear intensity variation is favoured for the longitudinal orientation to display a high quality of the continuous movement. Interestingly, this result reflects physiologist E.H Weber's

classical work on the tactile senses where tactile acuity is greater along the longitudinal orientation than transverse due to the main sensory nerves which run along the longitudinal axis of the upper limb[40].

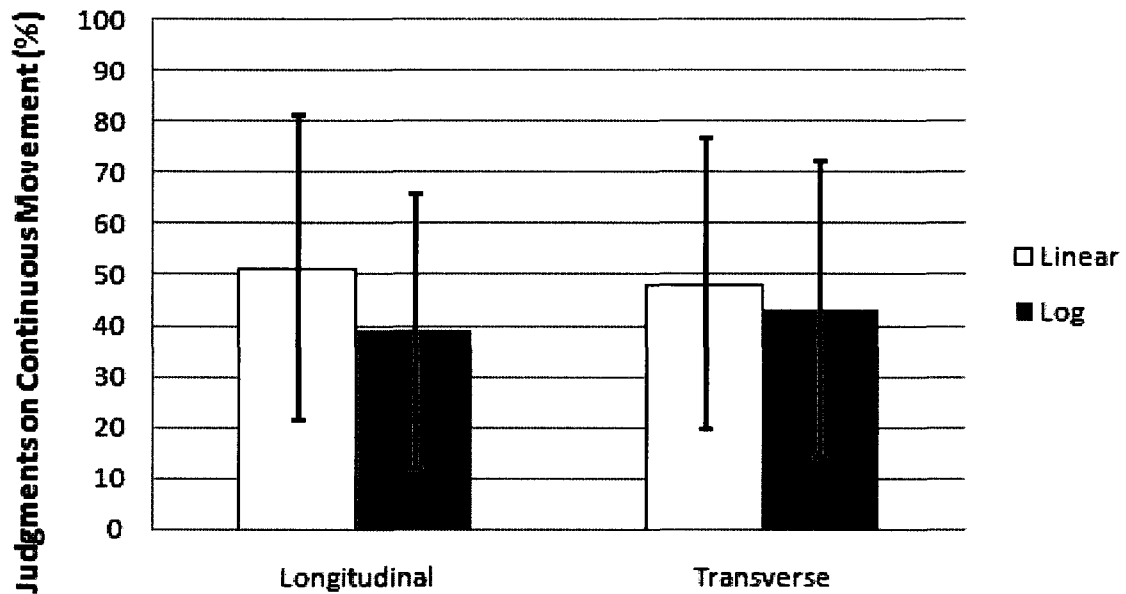


Figure 5.11: Mean judgments in percentage as a function of the interaction between the orientations and intensity variation with standard deviation

### 3. Main Effect for Limb Sites

Surprisingly, no main effect is shown for limb sites with ANOVA. Thus, the upper arm is not significantly different from the forearm on the quality of the continuous movement -  $F(1,1055)=0.5$ ,  $p=0.47$ . T-test results also show  $t(1054)=0.68$ ,  $p=0.24$ ; the limb sites make no significant difference on the quality of continuous movement. However, Weber[40] reports that the upper arm provides less tactile sensitivity than the forearm because the upper arm has more flesh and muscles compared to the forearm. Both extremities, however, possess lower tactile acuity when compared to the joints and glabrous skin regions for example [40]. Since both limb sites have lower tactile acuity this may reflect the findings of our ANOVA results.

#### 4. Main Effect for Gender

In our study, we attempted to evaluate and compare the judgments on quality of continuous movement between two genders (females and males). In regards to a high quality of continuous movement, females had the highest mean for linear intensity at 82% and males had the highest mean for logarithmic intensity at 60%; see Figure 5.12.

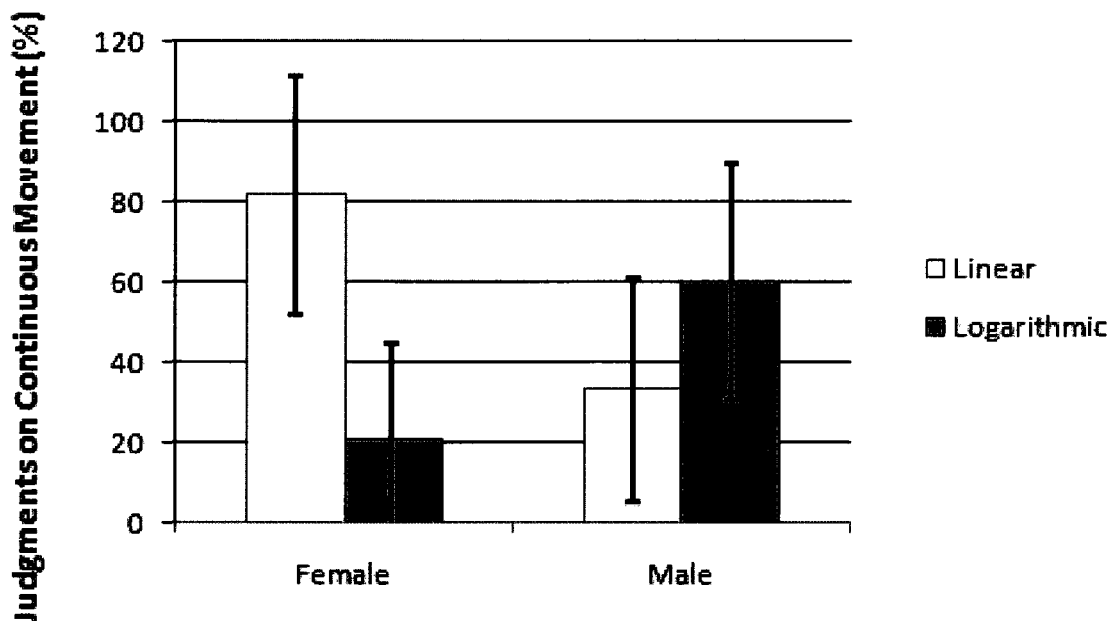


Figure 5.12: Mean judgments in percentage as a function of the interaction between the gender and intensity variation with standard deviation

A reason for these results can be due to the dimensions of the genders' upper limb. On average, forearm dimensions for the female upper limb were small, about 22x25 cm in circumference below the elbow and in length for the forearm, and 24x27cm circumference below the shoulder and in length of the upper arm. As a result, due to the small dimensions of the female upper limb, higher vibrotactile sensitivity to vibrations may result, as the vibrations are transmitted through the bone. Thus, females judged a higher quality for continuous movement and favoured linear intensity variations that provide a lighter intensity output.

As for the male subjects, the average dimensions of the male upper limb were large; the forearm was approximately 25x30cm in circumference below the elbow and in length, and the upper arm was 31x29 cm in circumference below the shoulder and in length. The large dimensions of the males' upper limb, which contains more flesh and muscle tissues, may result in a low vibrotactile sensitivity; thus, the males judged a lower quality for the continuous movement and preferred the logarithmic intensity, which provides a higher amplification output compared to the linear intensity.

The results shown by ANOVA, reveals no significant difference between the female group and male group towards the quality of the continuous movement,  $F(1, 1055)=0.28, p=1$ . The results is also observed in the T-test, where  $t(1055)=1.96, p=1$ ; thus the females and males are shown not to be significantly different. However seen by the results of a two-way ANOVA, the genders and intensity variations shows a significant difference of interaction,  $F(47,1055)=6.28, (p < 0.0001)$ . In the female group, linear intensity was preferable shown in the results of a T-test,  $t(417)=1.96, (p < 0.0001)$ ; thus the mean for linear intensity variation is significantly different from the mean for the logarithmic intensity variation. Also seen in male group, the logarithmic intensity variation was preferable,  $t(612)=1.96, (p < 0.05)$ , thus the mean for the logarithmic intensity variation is significantly different from the mean for the linear intensity variation.

### 5. Main Effect for Duration of the Stimulus (DOS)

The duration of the stimulus (DOS) was presented eleven times to the subjects with varying intensities to judge the quality of continuous movement. Figure 5.13 shows the results for the stimulus durations based on subjects judgments. Interestingly, we see a decrease in the quality of continuous movement as the DOS increases, and high means of the quality of continuous movement are present during the time frames of 100msec to 150 msec, reflecting the results in the literature [13, 29] for displaying optimum continuous movement between a DOS at 100msec to 200msec. As well, Figure 5.13 shows that a DOS of 110msec has the highest mean of 56% to the quality of continuous movement. As a result, for each of the four activated vibrotactile actuators, a DOS of 110 msec displays in total a 440msec continuous movement, which shows suitability for our proposed approach in providing a smooth and slow continuous movement. ANOVA revealed that DOS has a main effect on the quality of continuous movement, with a significant difference of  $F(10,1055)=7.88, (p < 0.0001)$ .

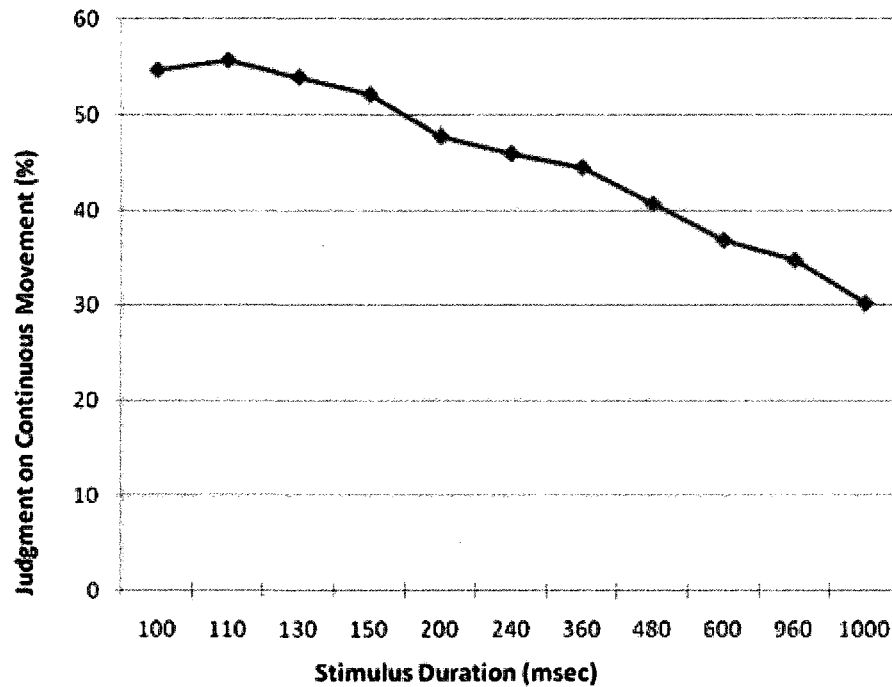


Figure 5.13: Mean judgments in percentage as a function of the stimulus duration

## POST HOC TEST

Using univariate ANOVA with SPSS, a Post Hoc test was performed using Tukey's multiple comparison test to determine which control conditions were significantly different from one another. From the multiple comparison table, see Appendix A.1, the plot shown in Figure 5.14 was formulated, displaying that there is a significance interaction between the genders (Female Male) and the control conditions (Forearm (FA), Linear, Longitudinal (LO), Transverse (TO) and Upper arm (UA)):  $F(5, 3167)=17.83$ , ( $p < 0.0001$ ), where a significance difference was only seen for the linear intensity and log intensity between the control conditions. Thus, the average female subject is strongly influenced by linear intensity variation and the average male subject is strongly influenced by logarithmic intensity in regards to the level of quality of continuous movement, as seen earlier.

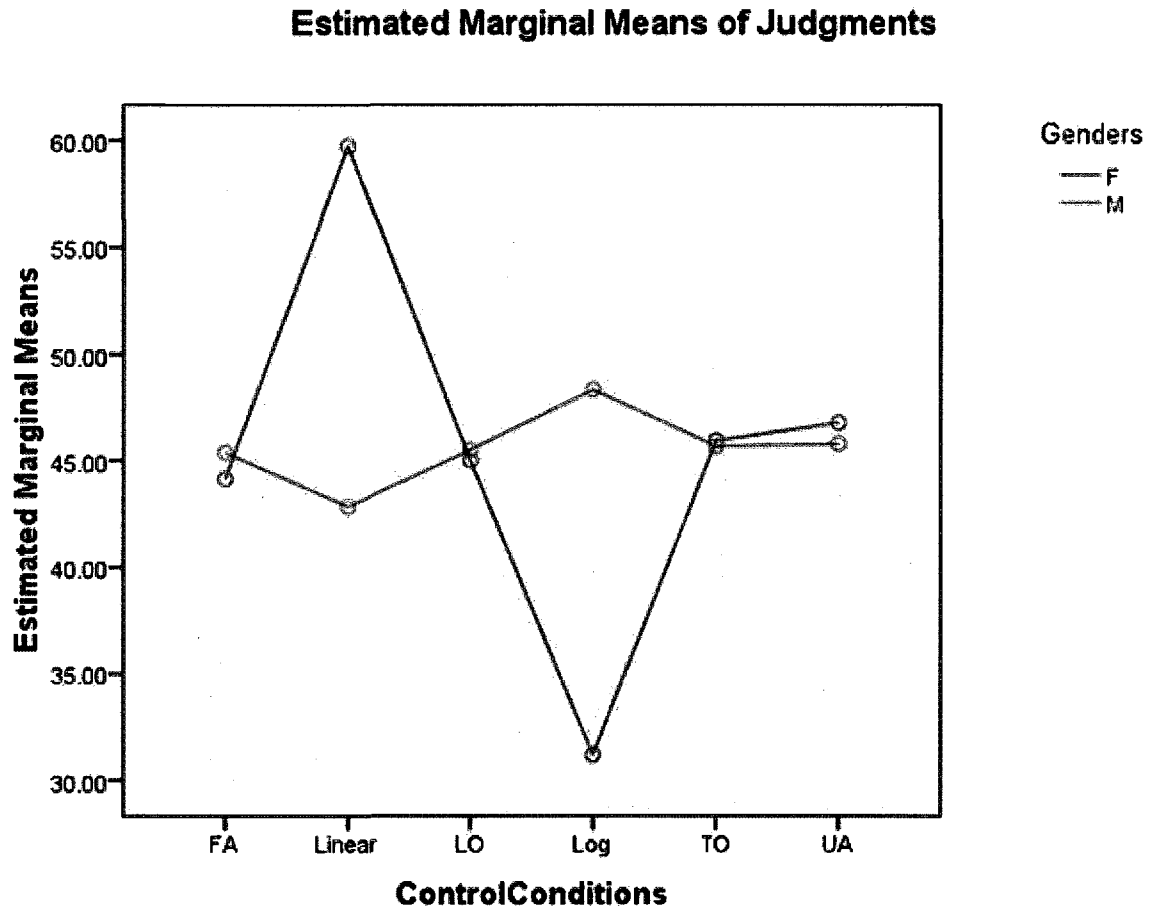


Figure 5.14: Mean judgments in percentage as a function of the interaction between genders and the control conditions

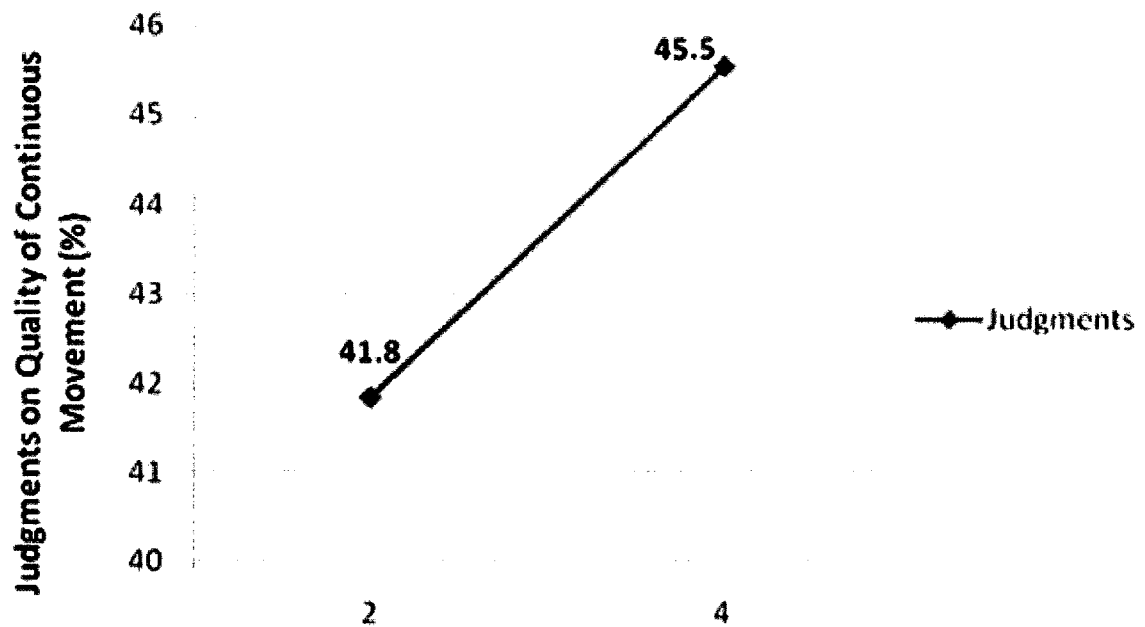


Figure 5.15: Mean judgments in percentage as a function of the number of actuators

We also looked into evaluating the participants' judgments on the quality of continuous movement as we increased the number of actuators from two in Experiment II to four in Experiment III. As can be seen from Figure 5.15, increasing the number of stimulators produced a slight higher percentage in judgments, where two actuators had a mean judgment of 41.8% and four actuators had a mean judgment of 45.5%. An explanation for the low judgments on the quality of continuous movement can be due to many factors; firstly, the forearm is a hairy skin region and since hair receptors have low spatial resolution they do not effectively detect a specific structure or movement across the skin as compared to glabrous skin regions, such as the palm of the hand and fingertips[27]. As a result, the upper limb (forearm and upper arm) possess low tactile acuity, which may affect judgments on the quality of continuous movement[40]. Nonetheless, based on the plot, there is a slight improvement of users' judgment in regards to the quality of continuous movement when increasing the number of actuators from 2 to 4.

## Discussion

A summary of the significant main effects and interaction effects are summarized in Table 5.4.

Table 5.4: Summary results of the main and interaction effects with repeated measures of ANOVA

	Intensity Variation	DOS	Limb Axis X Intensity Variation	Gender X Intensity Variation
Quality of Continuous Movement	F(1,1055)=24.28, ( $p < 0.0001$ )	F(10,1055)=7.88, ( $p < 0.0001$ )	F(1,1055)=4.7, ( $p < 0.05$ )	F(47,1055)=6.28, ( $p < 0.0001$ )

Overall, interesting ANOVA results show that the quality of continuous movement is affected by intensity variations and DOS, where the linear intensity variation and duration of the stimulus (DOS) at 110 msec provides the best possible continuous movement for all subjects. Significant difference of interaction is shown between intensity variation and gender, where males prefer logarithmic intensity variation and females prefer linear intensity variation. As well, a significant difference of interaction is seen between intensity variations and orientations. As a result, a high quality of continuous movement is dependent on two optimum control conditions: linear intensity variation and DOS at 110msec.

Thus, continuously moving touch sensation with four actuators is apparently perceived at an inter-stimulus distance of 50mm and a total duration of 440 msec, which is suitable for our proposed approach of displaying slow and smooth continuous sensation. Overall, interesting results show that the quality of continuous movement is affected by intensity variation and DOS, where a linear intensity variation and stimulus duration of 110 msec with four actuators at 50 mm distance provides the best possible continuous movement for all subjects.

Further investigation in the following section is performed to see which optimum logarithmic function is favourable for the male subjects to display a high quality of the continuous movement.

## 5.4 Psychophysical Experiment IV-Optimum Logarithmic Function

### 5.4.1 Goal

To finalize our psychophysical experiments, we prove the quality of the continuous movement is based on the two optimum control conditions (50mm distance and 110msec DOS) and determine the preferred logarithmic function for the male subjects.

### 5.4.2 Methodology

Twelve subjects from the University of Ottawa community participated, consisting of 6 males and 6 females, ranging in age from 23 to 29 years. The experimental set up was the same as in Experiment III, where the dimensions of the participants' forearm were measured to ensure central placement of the four actuators. Since there was no significance difference between the limb site and limb axis, the participants' inner forearm were tested along the longitudinal orientation for the experiment.

Referring to Equations (3.1) and (3.2), four different applied intensities were evaluated:

1. linear
2.  $(\log(1 + t * 5) / \log(1 + t_{max} * 5)) * \eta$ , for  $c=5$
3.  $(\log(1 + t * 10) / \log(1 + t_{max} * 10)) * \eta$ , for  $c=10$
4.  $(\log(1 + t * 20) / \log(1 + t_{max} * 20)) * \eta$ , for  $c=20$

where  $c$  = constant that controls the log intensity.

The intensities applied stayed within the preferred dynamic range where  $0 \leq \eta \leq \eta_{max} = 12$  and  $0 \leq t \leq t_{max} = 110msec$ .

Subjects reported that as the constant  $c$  from Equation (3.2) increased  $c=5,10,20$ , the applied intensity output perceived to be stronger. The intensities were applied in a random order and presented three times to the participants' inner forearms prior to judging

the quality of continuous movement. The experiment took approximately 35 minutes. Before the evaluation period, a training session was provided to help the participants become familiar with a high quality of continuous movement. A high quality of continuous movement was set at the optimum control conditions for each of the four actuators: DOS of 110msec and interstimulus distance of 50mm. Once subjects felt a high quality of the continuous movement based on perceiving a continuous movement of one tactile stimulus and not two separated stimuli as the criteria in literature [18], the evaluation session began.

## Results

During the evaluation session, qualitative measurements were taken by measuring the quality of the continuous movement based on a Likert scale questionnaire provided to the subjects. For each of the four applied intensities, subjects judged the quality of continuous movement based on a Likert scale questionnaire. Subjects' rated the questions from a scale of 1-5 (1: Strongly Disagree, 2: Disagree, 3: Neither Disagree nor Agree, 4: Agree, 5: Strongly Agree):

Q1: The quality of the continuous movement is clearly impressive with equal intensity, and one tactile stimulus is felt from the first vibrator to the last vibrator.

Q2: The quality of the continuous movement is present but is unimpressive, with a fade intensity at the midpoint between the first and last vibrator.

Q3: The quality of the continuous movement is felt as two separate stimuli.

Q4: The quality of the continuous movement is ambiguous and discrete.

Q5: No movement is experienced.

Figure 5.16 shows the mean responses of the subjects, both males and females, from a scale of 1-5.

As in the results in Experiment III, overall user judgment on the quality of continuous movement is favoured for linear intensity, with a high mean value of 4.5 to provide a clear and equal intensity of continuous movement.

Through questions 2 and 4, poor evaluations on the quality of the continuous movement is seen for the higher applied intensities,  $c=10$  and  $c=20$ .

Subjects reported to have felt more of a discontinuous movement as the  $c$  factor increased.

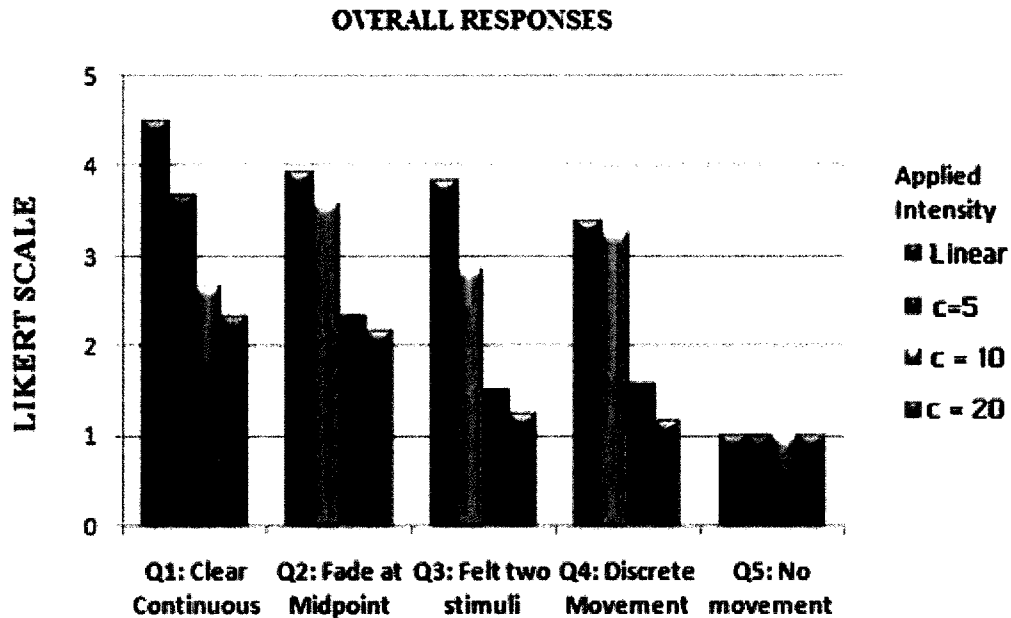


Figure 5.16: Quality of the continuous movement on the overall evaluation in the Likert scale

	Clear Continuous				Fade at Midpoint				Felt Two Stimuli			
Intensity	Linear	Log(5)	Log(10)	Log(20)	Linear	Log(5)	Log(10)	Log(20)	Linear	Log(5)	Log(10)	Log(20)
Mean	4.5	3.7	2.6	2.3	2.2	2.3	3.6	4	1.2	1.5	2.8	3.8
Std. Dev.	0.5	1.3	1.5	1.2	1.1	1.2	1.4	1.3	0.6	0.8	1.0	1.3
	Discrete Movement				No Movement							
Intensity	Linear	Log(5)	Log(10)	Log(20)	Linear	Log(5)	Log(10)	Log(20)	Linear	Log(5)	Log(10)	Log(20)
Mean	1.2	1.6	3.2	3.4	1	1	1	1				
Std. Dev.	0.4	0.8	1.3	1.3	0	0	0	0				

Figure 5.17: Quality of the continuous movement on the overall evaluation in the Likert scale with associated standard deviations

For question 5, subjects reported to experience no movement for any of the applied intensities. ANOVA revealed for the four applied intensities in question 1)  $F(3,47)=8.71$ , ( $p < 0.0001$ ) are significantly different. As well, a significant difference of  $F(3,47)=5.82$ , ( $p < 0.05$ ),  $F(3,47)=18.93$ , ( $p < 0.0001$ ) and  $F(3,47)=19.60$ , ( $p < 0.0001$ ) was seen between the four applied intensities for questions 2,3 and 4.

Figure 5.17 summarizes users overall performance scores with the associated standard

deviations.

In our study, we also attempted to evaluate the quality of continuous movement for the two genders, seeing which log function is favoured for males, shown in Figure 5.18.

The results show for question1, the average female subject favours linear intensity with a high mean of 4.8, while male subjects preferred the applied intensity  $c=5$  with a mean of 4.6. Although it can be seen that there is only a slight difference for the male groups favouring the applied intensity for  $c=5$  over the linear intensity. By summing the results for the female and male responses overall users favours the linear applied intensity to display a clear and equal intense continuous movement which contradicts the works of Alles.

Thus, the applied intensity  $c=5$  is the favourable logarithmic function for male subjects in regards to displaying a clear and equal intense continuous movement as compared to the higher intensity log functions. Observed by the results of a two-way ANOVA, no significant difference is seen between the female and male groups, where  $F(1, 239)=3.64$ ,  $p=0.0575$ . However a significance of interaction is seen between the genders and the four applied intensities, where  $F(1, 239)=8.25$ , ( $p < 0.0001$ ).

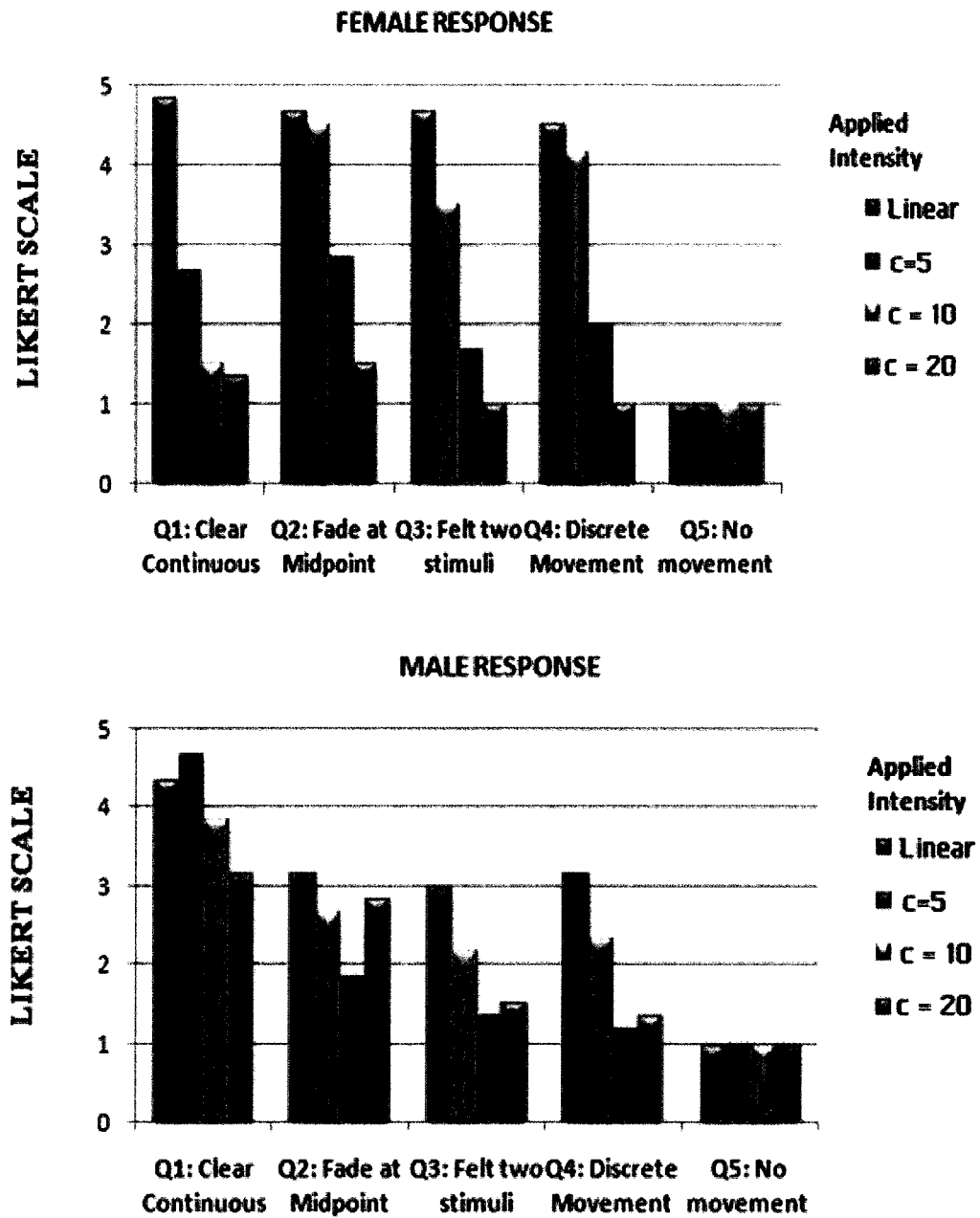


Figure 5.18: Females and Males responses on the evaluation of the quality of the continuous movement in the Likert scale

## Discussion

Overall, the responses from the Likert scale show high quality means towards question 1 which is to provide a clear and equally intense continuous movement. Based on all the subjects' responses, a linear intensity variation is favoured as providing the best possible continuous movement. However, evaluating the two genders, it is clear that females prefer linear variation whereas males favour logarithmic variations, reflecting the results in Experiment I. Additionally, we obtain an optimum logarithmic function for the males, for the applied logarithmic intensity  $(\log(1 + t * 5)/\log(1 + t_{max} * 5)) * \eta$ , for  $c=5$  is the most favourable for displaying continuous movement.

By looking at the two groups, females show more sensitivity to tactile applied intensities compared to males, since the females provided higher ratings on the quality of continuous movement. Again, this observation can be due to the dimensions of the females' and males' forearms, as the average male subjects tested in the experiment had larger forearm dimensions containing more muscle tissue, compared to the average female; this could account for lower vibrotactile acuity to continuous movement. Thus, we propose a continuous movement with discrete vibrotactile actuators which will increase the readability of information presented by vibrotactile devices while maintaining minimum hardware. A summary of the optimum control parameters are shown in Table 5.5.

Table 5.5: Optimum control conditions for continuous vibrotactile movement

Number of Actuators	Temporal Order	Amplitude Variation	Distance
4	DOS=110msec	Linear Intensity	50 mm

# Chapter 6

## Conclusion and Future Work

### 6.1 Conclusion

In this thesis, we presented a dynamic tactile sensation for low resolution vibrotactile displays. Our proposed method uses a human sensory illusion to produce high resolution, continuous movement on the human skin with discrete vibrotactile actuators on a wearable tactile display.

We investigated the critical parameters of the psychophysical funnelling illusion movement sensation. The influence on the temporal intensity variation in a linear and logarithmic pattern between the number of actuators were evaluated according to the favored distance, temporal order, orientation and limb site. Based on psychophysical tests, subjects' responses to the optimum continuous movement are seen with four vibrotactile actuators for the linear intensity variation at an interstimulus distance of 50 mm and a DOS of 110 msec.

Surprisingly, with two actuators, subjects favored the linear intensity variation at the 50mm distance; however, the quality of the continuous movement was greater as the number of actuators increased from two to four. Thus, with four vibrotactile actuators, we can provide suitability to propose high resolution continuous movement with discrete vibrotactile actuators while maintaining minimum hardware.

Statistical analysis revealed a significance difference of interaction between intensity variation and genders  $F(47,1055)=6.28$ , ( $p < 0.0001$ ) where females favored the linear intensity variation and males favored the logarithmic variation.

Additionally, from the Likert Scale, we observed that the average male subjects favored the logarithmic intensity of  $(\log(1 + t * 5) / \log(1 + t_{max} * 5)) * \eta$ , for  $\eta=5$  to display the optimum continuous movement. Although, overall users responses favours the linear applied intensity to display a a clear and equal intense continuous movement which contradicts the works of Alles[9].

Moreover, for limb axis a significant interaction effect between limb axis and intensity variation was shown  $F(1,1055)=4.7$ , ( $p < 0.05$ ), where linear intensity variation is favorable for the longitudinal and transverse orientations at the 50mm distance. As well a significant difference of  $F(1,1055)=24.28$ , ( $p < 0.0001$ ) was found between the intensity variations where a linear intensity variation is favored and for DOS a significance difference of  $F(10,1055)=7.88$ , ( $p < 0.0001$ ), where a DOS at 110 msec is favored to display the best possible continuous movement for all subjects. However, no significant differences were found between the limb sites, which include the upper arm and forearm and limb axis, which include the transverse and longitudinal orientations.

Overall, these results will allow us to design tactile displays with high resolution, continuous moving vibrotactile stimuli to increase the readability of information for tactile devices.

### 6.1.1 Limitations

Limitations facing our prototype include the design of the vibrotactile system and technologies used to implement the system. Much ongoing research has designed sophisticated, wearable tactile devices with wireless capabilities to provide remote access to the wearer. Bluetooth capabilities will be further explored for future development.

An additional limitation is size of the vibrotactile system. Advancements to the hardware of the vibrotactile system should be considered by minimizing the design of the vibrotactile system into a single unit, where the technologies of the system, such as the MCU, bluetooth chip, power supply and vibrotactile actuators are integrated. The miniaturization of the vibrotactile system can be embedded anywhere on a wearable material and provide optimum flexibility to the wearer.

While our proposed methodology successfully achieved to display optimum continuous movement along the human skin, there are several facets which can be examined for future developments.

## 6.2 Future Work

The future additions to the vibrotactile system are enumerated as follows:

1. **Comparison of Tactile Actuators:** Investigation with additional tactile actuators should be considered to display continuous movement sensations. Particularly, voice coil actuators, which provide a faster response time than DC vibrating actuators, should be tested. Future research must also look into pneumatic and hydraulic actuators which use air and fluids to produce tactile stimuli, useful for exoskeleton haptic devices.
2. **Stimulus Range and Smart fabrics:** Although the vibrotactile system focuses primarily on touch stimulation (haptics), this does not preclude the future use of alternative sense stimulation such as sound, vision and smell when integrated with correct electronics. Smart fabrics should be deployed in the advancements of the wearable tactile display. Examples include conductive yarns and metallic silk organza, which allow electronic components to be sewn together and become virtually invisible in clothing by replacing electronic wires; flexible materials with imprinted microprocessors that are made to be sewn into garments; fabrics that react to their environment that may act as sensors; textiles that convert ambient energy sources to provide power for other system components[32]. Additionally, MP3 players and global positioning systems (GPS) are now being integrated in clothes by Infineon[4]. These innovations are part of the focus of current textile research, and future research must consider traditional clothing selection criteria (durability, comfort and fashion) for wearable tactile displays.
3. **Power Supply:** Miniaturization of power supplies should be looked into for wearable tactile displays. Examples are the Printed Battery by Power Paper[7] and the Power Fiber by ITN Energy System[6]. These wearable energy sources are thin and flexible power sources which provide high voltage power capabilities and can be easily sewn into clothing.

4. **Haptic Jacket:** The major future advancement of this research is to provide the “sense of touch” to a wearable vibro-tactile device known as the Haptic Jacket. The Haptic Jacket is integrated with a synchronous haptic-audio-visual teleconferencing system (Hug Me system) which enables people to exchange physical stimuli over a network wearing the Haptic jacket. The Hug Me System is a patent project and the Haptic Jacket focuses on displaying real time, continuous movement sensations over the network to deliver hugs and touch information to a remote wearer.

The Haptic Jacket, embedded with vibrotactile actuators, is capable of simulating the sense of touch; the design is displayed by the use of a network of tiny vibrotactile actuators (same as in the vibrotactile system) distributed over a flexible material. In order to simulate the feeling of touch, specific actuators are controlled in a manner by the funnelling illusion to display the real touch or touch stroke.[23]

In addition, temperature actuators such as thermoelectric coolers (TECs) using the Peltier Effect is currently being explored to simulate the warmth of touch[5].

Figure 2 shows the haptic jacket that is embedded with arrays of vibrotactile actuators. The arm part of the jacket is integrated with a zipper and as the zipper is opened, the array of vibrotactile actuators are attached by Velcro material and secured snaps in the inner layer of the jacket. The inner fabric prevents any direct harm to the wearer from the vibrotactile actuators and the electrical wires. The same design was performed for the chest area of the jacket.[23]

The display of the funnelling illusion and the perceptual parameters determined in this research thesis (which is the spatial resolution of 50mm distance, temporal order of DOS 110msec and a linear intensity variation) will be applied to the vibrotactile actuators embedded into the Haptic Jacket to deliver realistic hugs and touch information for the HugMe system. Future examination will consider measuring the quality of a realistic hug over the network. The Haptic Jacket can be used in a variety of applications, such as instant messaging, gaming, medical practices and military, providing wearers with a more “human-like computer interaction.”

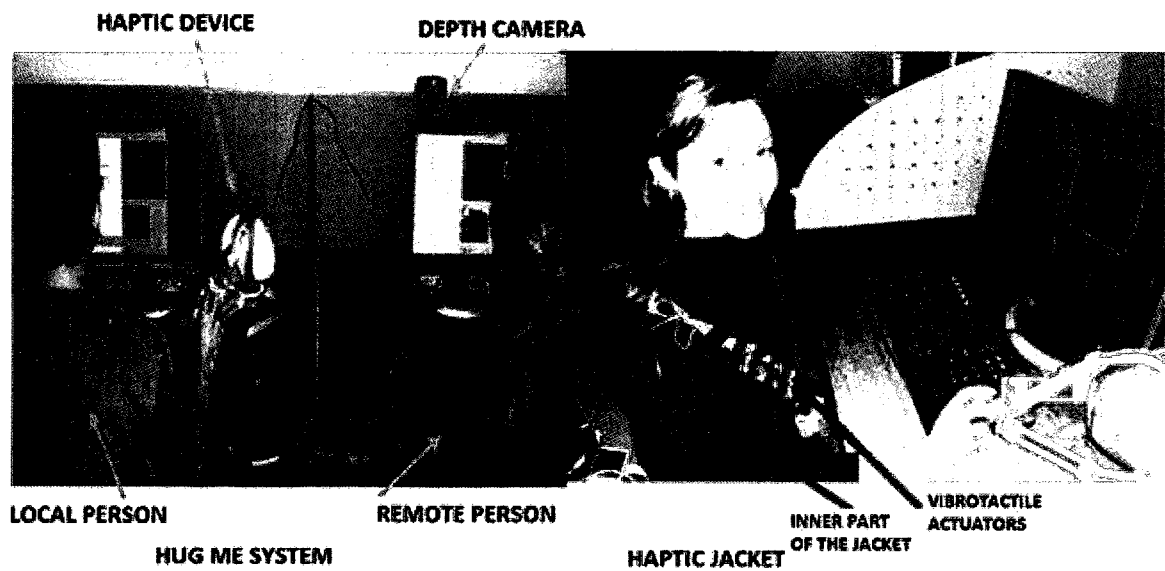


Figure 6.1: Hug Me System and Haptic Jacket

# **Appendix A**

## **Appendix**

### **A.1 Multiple Comparison Table**

See Figure A.1 for the Multiple Comparison Table using univariate ANOVA with SPSS.

### **A.2 University of Ottawa Ethical Approval**

### **A.3 Informed Consent Form**

Please refer to the documents attached at the back of this thesis for the University of Ottawa Research Ethical Board Approval and Consent Form.

Judgments  
Tukey HSD

(I) Control conditions	(J) Control conditions	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
FA	Linear	-5.0167	1.78271	.055	-10.1001	.0666
	LO	-.4183	1.78271	1.000	-5.5016	4.6650
	Log	3.6811	1.78271	.306	-1.4023	8.7644
	TO	-.9174	1.78271	.996	-6.0007	4.1659
	UA	-1.3357	1.78271	.976	-6.4190	3.7477
Linear	FA	5.0167	1.78271	.055	-.0666	10.1001
	LO	4.5984	1.78271	.103	-.4849	9.6818
	Log	8.6978	1.78271	.000	3.6144	13.7811
	TO	4.0993	1.78271	.194	-.9840	9.1827
	UA	3.6811	1.78271	.306	-1.4023	8.7644
LO	FA	.4183	1.78271	1.000	-4.6650	5.5016
	Linear	-4.5984	1.78271	.103	-9.6818	.4849
	Log	4.0993	1.78271	.194	-.9840	9.1827
	TO	-.4991	1.78271	1.000	-5.5824	4.5842
	UA	-.9174	1.78271	.996	-6.0007	4.1659
Log	FA	-3.6811	1.78271	.306	-8.7644	1.4023
	Linear	-8.6978	1.78271	.000	-13.7811	-3.6144
	LO	-4.0993	1.78271	.194	-9.1827	.9840
	TO	-4.5984	1.78271	.103	-9.6818	.4849
	UA	-5.0167	1.78271	.055	-10.1001	.0666
TO	FA	.9174	1.78271	.996	-4.1659	6.0007
	Linear	-4.0993	1.78271	.194	-9.1827	.9840
	LO	.4991	1.78271	1.000	-4.5842	5.5824
	Log	4.5984	1.78271	.103	-.4849	9.6818
	UA	-.4183	1.78271	1.000	-5.5016	4.6650
UA	FA	1.3357	1.78271	.976	-3.7477	6.4190
	Linear	-3.6811	1.78271	.306	-8.7644	1.4023
	LO	.9174	1.78271	.996	-4.1659	6.0007
	Log	5.0167	1.78271	.055	-.0666	10.1001
	TO	.4183	1.78271	1.000	-4.6650	5.5016

Based on observed means.

The error term is Mean Square(Error) = 839.008.

\*. The mean difference is significant at the .05 level.

Figure A.1: Multiple Comparison Table

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**Université d'Ottawa**    **University of Ottawa**  
 Service de subventions de recherche et déontologie    Research Grants and Ethics Services

**Ethics Approval Notice**  
**Health Sciences and Science REB**

**Principal Investigator / Supervisor / Co-investigator(s) / Student(s)**

<u>First Name</u>	<u>Last Name</u>	<u>Affiliation</u>	<u>Role</u>
Jongeun	Cha	Engineering / Electrical Engineering	Principal Investigator
Lara	Rahal	Engineering / Electrical Engineering	Co-investigator

**File Number:** H02-09-12

**Type of Project:** Master's Thesis

**Title:** Simulating Continuous Movement with Four Vibrating Motors on the Human Skin

<b>Approval Date (mm/dd/yyyy)</b>	<b>Expiry Date (mm/dd/yyyy)</b>	<b>Approval Type</b>
05/28/2009	05/27/2010	Ia

(Ia: Approval, Ib: Approval for initial stage only)

**Special Conditions / Comments:**

N/A



**Université d'Ottawa** **University of Ottawa**  
Service de subventions de recherche et déontologie      Research Grants and Ethics Services

This is to confirm that the University of Ottawa Research Ethics Board identified above, which operates in accordance with the Tri-Council Policy Statement and other applicable laws and regulations in Ontario, has examined and approved the application for ethical approval for the above named research project as of the Ethics Approval Date indicated for the period above and subject to the conditions listed the section above entitled "Special Conditions / Comments".

During the course of the study the protocol may not be modified without prior written approval from the REB except when necessary to remove subjects from immediate endangerment or when the modification(s) pertain to only administrative or logistical components of the study (e.g. change of telephone number). Investigators must also promptly alert the REB of any changes which increase the risk to participant(s), any changes which considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project and safety of the participant(s). Modifications to the project, information/consent documentation, and/or recruitment documentation, should be submitted to this office for approval using the "Modification to research project" form available at:  
[http://www.rges.uottawa.ca/ethics/application\\_dwn.asp](http://www.rges.uottawa.ca/ethics/application_dwn.asp)

Please submit an annual status report to the Protocol Officer 4 weeks before the above-referenced expiry date to either close the file or request a renewal of ethics approval. This document can be found at:  
[http://www.rges.uottawa.ca/ethics/application\\_dwn.asp](http://www.rges.uottawa.ca/ethics/application_dwn.asp)

If you have any questions, please do not hesitate to contact the Ethics Office at extension 5841 or by e-mail at: [ethics@uOttawa.ca](mailto:ethics@uOttawa.ca).

Pierre Ndoumaï  
Protocol Officer for Ethics in Research  
For Dr Daniel Lagarec, Chair of the Health Sciences and Sciences REB

## Consent Form

**Title of the study:** Design and development of continuous movement algorithms with vibrotactile actuators

**Name of Co-researcher:** Lara Rahal, Master Electrical Engineering Graduate Researcher  
**Affiliation:** SITE (School of Information and Technology Engineering) of the University of Ottawa \*

**Supervisor:** Abdulmotaleb El Saddik

**Affiliation:** School of Information Technology and Engineering (*SITE*), University of Ottawa 800 King Edward, Ottawa, Ontario, Canada, K1N 6N5

**Principal Investigator:** Dr. Jongeun Cha

**Invitation to Participate:** I am invited to participate in the above mentioned research study conducted by the researcher Lara Rahal where this project is funded by NSERC.

**Agencies Financing the Research:** NSERC

**Purpose of the Study:** The purpose of the study is to determine optimum continuous movement with four vibrating motors on the human skin to produce realistic touch over the network or have the vibration movement to act as a navigation guide for haptic technologies.

**Participation:** My participation will consist essentially of attending 1 session where the experiment will take approximately 35 minutes during which you as a participant will answer to a questionnaire through a user interface to rate the quality of the continuous movement. The session has been scheduled (\_\_\_\_\_AM/PM and 2009) at Location of the research work: The Multimedia Communications Laboratory on the 5th floor Colonel By Hall Building (room: B 505). I will also be asked to fill in a questionnaire, see below:

**QUESTIONNAIRE:** A (EXCELLENT): Clearly experienced an impressive and continuous movement along your skin from one stimulating point to the other.

B (AVERAGE): The experience movement was present but was either discontinuous between the two endpoints (two last vibrating motors)

C (POOR): The movement was very discrete

ZERO: There is no movement

**Risks:** My participation in this study will entail that you rate the quality of the continuous movement with the vibrating actuators and this may cause me to feel not to tolerate the light vibrations of the motors. I have received assurance from the researcher that every effort will be made to minimize these risks the participant has the right to stop from the experiment at any time.

**Benefits:** My participation in this study will benefit in the study of HAPTICS to deliver the sense of touch for Haptic technologies. Producing continuous motion with vibrating actuators will benefit the blind or military troops to act as a navigation guide when integrated with haptic technologies.

**Confidentiality and anonymity:** I have received assurance from the researcher that the information I will share will remain strictly confidential. I understand that the contents will be used only for and that my confidentiality will be protected. All participants' results are recorded anonymously and will be recorded through software and will stay confidential and protected on a computer. **Anonymity** will be protected in the following manner by recording all users' results anonymously.

**Conservation of data:** Only electronic data will be collected through a user interface where the results of the questionnaire are recorded anonymously through software and will be kept in a secure manner and stored in a computer where only the researcher Lara Rahal will have access to. The results are kept reserved until the project is finalized afterwards the results will be deleted.

**Voluntary Participation:** I am under no obligation to participate and if I choose to participate, I can withdraw from the study at any time and/or refuse to answer any questions, without suffering any negative consequences. If I choose to withdraw, all data gathered until the time of withdrawal will be destroyed data.

**Acceptance:** I, \_\_\_\_\_ agree to participate in the above research study conducted by *Lara Rahal* of the School of Information and Technology Engineering, *which research is under the supervision of Abdulmotaleb El Saddik.*

If I have any questions about the study, I may contact the researcher or her supervisor.

If I have any questions regarding the ethical conduct of this study, I may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 159, Ottawa, ON K1N 6N5  
Tel.: (613) 562-5841  
Email: ethics@uottawa.ca

There are two copies of the consent form, one of which is mine to keep.

Participant's signature: \_\_\_\_\_ Date: \_\_\_\_\_

Witness (*needed in the case where a participant is illiterate, blind, etc.*):  
Signature : \_\_\_\_\_ Date: \_\_\_\_\_

Researcher's signature: \_\_\_\_\_ Date: \_\_\_\_\_