Factors Affecting Human Force Perception and Performance in Haptic-Enabled Virtual Environments

by

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Abstract

Haptic technology enables computer users to touch and/or manipulate virtual objects in virtual environments (VEs). Similar to other human-in-the-loop applications, haptic applications require interactions between humans and computers. Thus, human-factors studies are required to recognize the limitations and capabilities of the user. This thesis establishes human-factors criteria to improve various haptic applications such as perception-based haptic compression techniques and haptic-enabled computer-aided design (CAD).

Today, data compression plays a significant role in the transmission of haptic information since the efficient use of the available bandwidth is a concern. Most lossy haptic compression techniques rely on the limitations of human force perception, and this is used in the design of perception-based haptic compression techniques. Researchers have studied force perception when a user is in static interaction with a stationary object. This thesis focuses on cases where the human user and the object are in relative motion. The limitations of force perception are quantified using psychophysical methods, and the effects of several factors, including user hand velocity and sensory adaptation, are investigated. The results indicate that fewer haptic details need to be calculated or transmitted when the user's hand is in motion.

In traditional CAD systems, users usually design virtual prototypes using a mouse via their vision system only, and it is difficult to design curved surfaces due to the number, shape, and position of the curves. Adding haptics to CAD systems enables users to explore and manipulate virtual objects using the sense of touch. In addition, human performance is important in CAD environments. To maintain the accuracy, active haptic manipulation of the user response can be incorporated in CAD applications. This thesis investigates the effect of forces on the accuracy of movement in VEs. The results indicate that factors such as the base

force intensity and force increment/decrement can be incorporated in the control of users' movements in VEs. In other words, we can pull/push the users' hands by increasing/decreasing the force without the users being aware of it.

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Dedication

Dedicated to Fariba, Parastou, Ava, and Fakhrieh

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Chapter 1

Introduction

1.1 Motivation and Objectives

In everyday life, we have physical experiences such as resistance to movement, texture, and stiffness through our sense of touch. To experience these properties in virtual environments (VEs), computer interfaces are required to enable users to interact with virtual objects. Haptic technology enables computer users to touch and/or manipulate virtual or remote objects in simulated environments or teleoperation systems. If haptic cues (e.g. touch sensations) are displayed in addition to visual and auditory cues, these VEs are called haptic-enabled virtual environments (HEVEs) [1]. This thesis presents a detailed investigation into factors that affect the realism of HEVEs when the user is in motion within HEVEs.

Haptic research is intrinsically multi-disciplinary, incorporating computer science/engineering, control, robotics, psychophysics, and human motor control. By extending the scope of research in haptics, advances can be achieved in existing applications such as computer-aided design (CAD), tele-surgery, rehabilitation, scientific visualization, robot-assisted surgery, authentication, and graphical user interfaces (GUI) to name a few. Thus, the potential benefits of research in this area are far reaching.

Haptic-enabled virtual reality (VR) applications require interactions between humans and computers. Due to the complexity and variability of the user's physical motion, it is difficult to generate a precise mathematical description of human motor control behaviour [2]. It is also very difficult to mathematically model both the user's hand and the interaction among the hand, the haptic device, and virtual objects. Thus, human-factors studies are required to recognize the limitations and capabilities of the user.

This study provides the necessary foundation to incorporate human factors into various haptic applications such as perception-based haptic compression techniques and haptic-enabled computer-aided design.

1.1.1 Perception-based Haptic Compression Techniques

The ability of technology to transmit multi-media content is very dependent on compression techniques since bandwidth affects how much information can be transmitted in a given amount of time. Researchers have investigated efficient lossy compression techniques for image compression (jpeg) [3], audio compression (mp3) [4, 5] and video compression (mpg) [6] to facilitate the storage and transmission of audio and video. Recently, haptics is becoming more important with its addition in computer games [7] or in cruder applications such as vibrations in a cell phone [8]. As haptic technology improves, the ability to transmit compressed force sensations becomes more important. Most lossy audio and visual compression techniques rely on the lack of sensitivity in humans to pick up detailed information in certain scenarios. Similarly, limitations in the sensitivity of human touch could be exploited to create haptic models with much less detail and thus requiring less bandwidth for a given sensation.

In this thesis, the limitations of human force perception is quantified using psychophysical methods. Knowledge about force perception can be used in perception-based haptic compression techniques. Most of the research in this field studied force perception with a human user in static interaction with a stationary rigid object [9, 10, 11]. This thesis focuses on cases where the human user or the object are in relative motion. In addition, the effects of several factors, including user hand velocity and sensory adaptation, on force threshold are investigated.

1.1.2 Haptic-enabled Computer-aided Design

In real environments, designers interactively design 3D shapes via their vision system and sense of touch. In other words, they see and touch a model in order to modify its surface. However, in a traditional CAD system, a user usually grasps an input device (e.g. a 2D mouse) to explore the environment. A tool tip (e.g. arrow or cross-hairs) usually represents the user's hand in the display, which allows the user to maintain his/her movement and accuracy using visual cues only.

It is very difficult to achieve the full modelling potential associated with the physics-based design framework required in many applications such as the design of automobile bodies and industrial products using visual cues only [12]. In these applications, the design of curve surfaces is difficult due to the number, shape, and position of the section curves that the designer has to deal with. To overcome these problems, researchers [12, 13, 14, 15] have developed haptic-based CAD systems, showing a significant improvement in the design of models.

In a haptic-enabled CAD system, designers explore and manipulate virtual objects using the sense of touch. Designers grasp the end-effector of a haptic device and interact with the virtual objects in the design environment. Figure 1.1 shows a

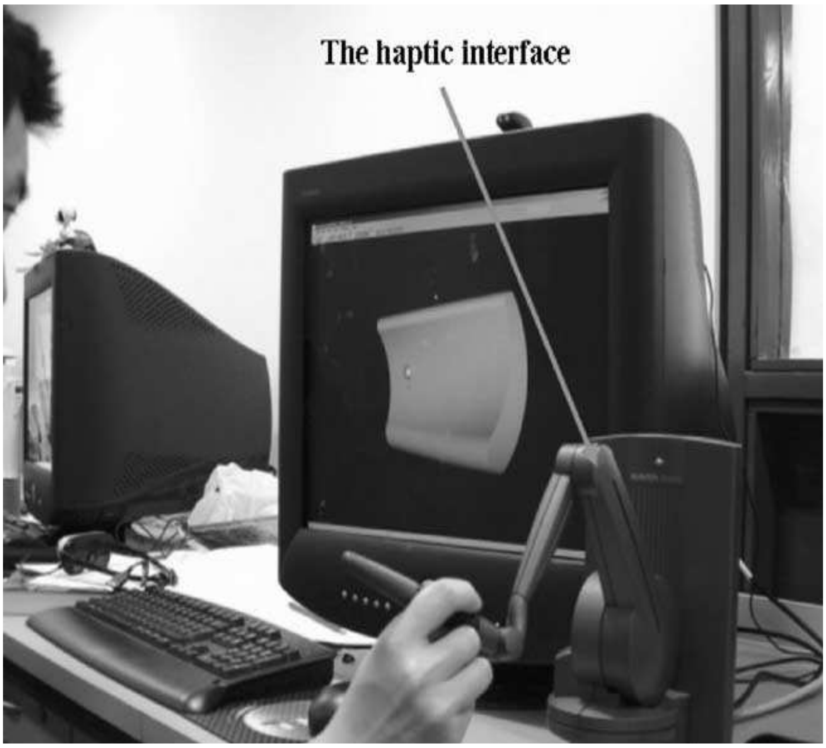


Figure 1.1: Computer-aided design using a haptic device [13].

haptic-enabled computer-aided design system. The haptic device should present appropriate force feedback to the designers' hands based on their movement. Haptic-enabled VEs are also used in a variety of applications such as computer-aided assembly [16, 17] and computer-assisted surgery [18].

Human performance is important in most VR applications [19]. The accuracy of movement is one of the most important measures in the study of user performance [20]. To maintain the accuracy of a user's movement, active manipulation of the user response can be incorporated in VR systems. Force feedback can be utilized to pull or push the users' hands to aid them in their task. For instance, McGee [21] added force feedback to a scroll bar in a search task. She presented a gravity well, which was a 0.5 N force that forced the subject's hand to stay on the centre of a button. The gravity well prevented the user from accidentally slipping off the button, and her results showed improvement in the accuracy of movement [21].

Similarly, force feedback can be used in tasks such as the drawing or manipulating of lines or curves in CAD environments. For example, Figure 1.2 shows the difficulty of quickly drawing a curve using CAD software (AutoCAD [22]). Due to needing to have the cursor almost exactly on the curve before manipulating the lines, it is difficult to control the hand to such a fine precision quickly. As a result, the user's hand may miss the target curve and draw a curve in a wrong position. Suppose the CAD software can present forces to the user; changes in the intensity and direction of forces can help the user to control his or her hand on the curve to be manipulated. The user can quickly reach the desired target and accurately stay on the target until the task is done. To push the user's hand, forces would be applied in the same direction as the hand motion. We can also apply forces opposed to the direction of motion to avoid slipping off the cursor. In addition, we can change force intensity to smaller increments or decrements to keep controlling the user's hand for finer adjustments.

Moreover, the users should not feel an unnatural pulling or pushing that is contrary to their real-world experiences. This could cause the user to *fight* the effects or could be a barrier to the adoption of these aids because they feel unnatural to the user. To achieve this goal, sub-threshold forces can be incorporated in assisting the users in these tasks. The sub-threshold forces cannot be perceived by the user since they are below the force threshold of human force perception, even though they may be providing improved performance in these tasks. It is therefore essential to know the thresholds of human force perception to find a valid range of sub-threshold forces. Psychophysical methods can be used to ensure that the applied forces are smaller than the difference force threshold or just noticeable difference (JND), which is the minimum difference between two force stimuli that is necessary to be reliably perceived [23].

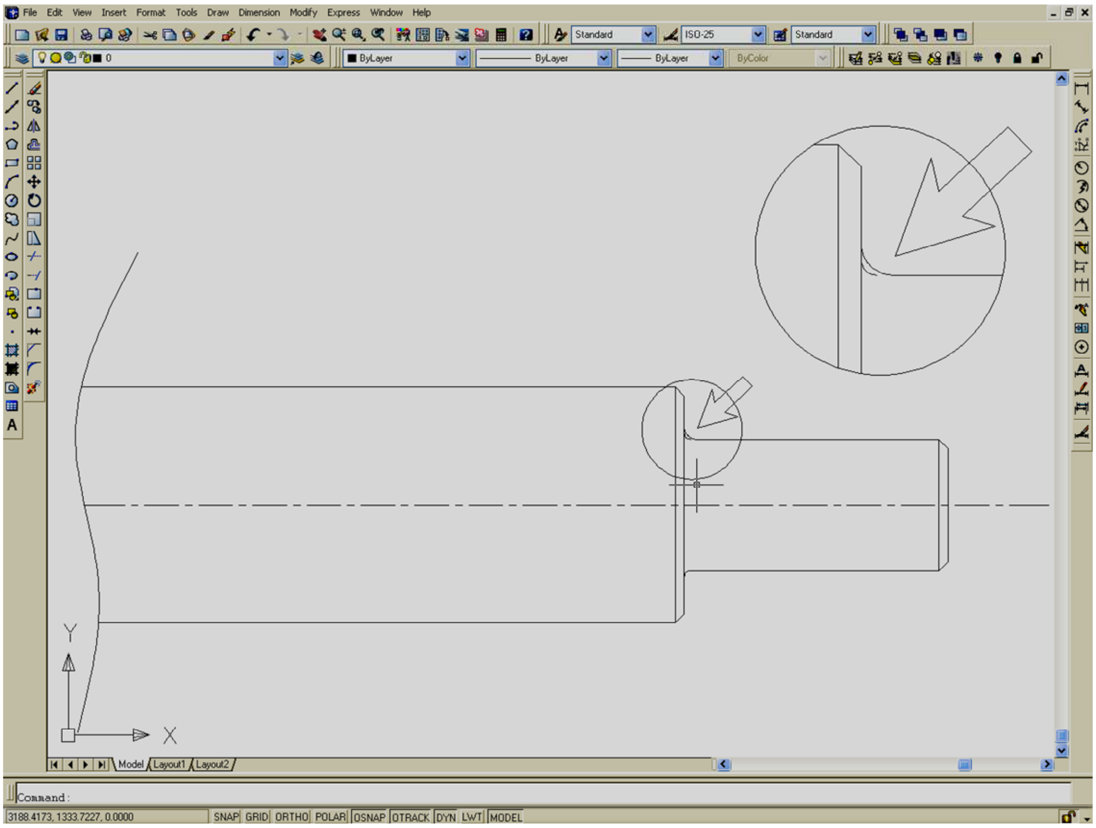


Figure 1.2: The designer wrongly drew two curves due to slipping of the cursor in AutoCAD [22] because it was difficult to control the hand to such a fine precision.

The motion of a user's hand is important in many applications (e.g. CAD), and the limitations and capabilities of human motor control should be studied using reliable models [2]. Thus, human-factor studies are required for understanding the properties of human motor control behaviour. For example, Fitts [24] developed a tapping task to systematically analyze the relationship between accuracy and speed. The Fitts task is explained in detail in Section 2.1.1.

In this thesis, a multi-modal task is defined for a subject interacting with a VE based on the Fitts task . The subject engaged in a task that is similar to the Fitts task. The multi-modal task is used to evaluate subject performance in the presence of forces that are below the force JND of the human force perception. Essentially, the effects of unnoticed haptic effects are investigated in the presence of visual cues. A performance index is proposed to evaluate user performance in the application of sub-threshold forces.

1.2 Major Contributions

The main objective is to study the limitations and capabilities of user force perception and motor control when the user's hand and virtual objects are in motion. The results of this study provide human factors that can be incorporated into the development of haptic displays and various applications such as haptic compression techniques and computer-aided design.

Chapter 3 presents an approach of incorporating the user's hand velocity as the part of the process of measuring the difference force threshold. The results show that the difference force threshold increases as the velocity of the user's hand increases in an HEVE, indicating that fewer haptic details are required to be stored, calculated or transmitted when a user's hand is in motion.

The adaptation of human force perception to forces in an HEVE is investigated in Chapter 4. Based on the results, users lose sensitivity to applied forces in a VE when they are using haptic devices for an extended period of time. Researchers can use this result to design experimental procedures in force perception studies when forces are applied on subjects' hands for a period of time.

The effects of forces on user accuracy are also studied in Chapter 4. The results show that sub-threshold forces can affect user performance in HEVEs such as computer-aided design environments. Forces pull/push the user's hand by increasing/decreasing the force intensity. The results also show that the usual index performance and missing error of the Fitts task do not show the effects of forces on accuracy. Instead, the difference between the overshoot and undershoot errors should be used as a performance index to quantify user accuracy in the application of forces.

The measured JNDs in Chapter 4 can be used in the haptic display of VEs when the user's hand is in motion. The JNDs can be used to set the resolution of haptic displays. The knowledge about the effects of factors such as the base force intensity and force increment/decrement can also be used in the haptic display of VEs.

1.3 Thesis Outline

The thesis is organized as follows;

Chapter 2 starts with basic background of HEVEs and haptics terminology, followed by a review of important factors in the haptic display of VEs. This chapter also reviews the human factors in VEs, including the limitations and capabilities of human force perception and the human performance. Fitts' task is also explained in detail and relevant previous research is surveyed. In addition, Weber's law, sensory thresholds and several classical psychophysical methods are also explained, and previous work on the human haptic system is reviewed.

Chapter 3 presents an approach to incorporating velocity in the process of measuring the difference force threshold. First, the friction of haptic device is estimated to find the base force of difference force threshold. Then, an HEVE is constructed to study the effect of user's hand velocity on force perception. Further, the force thresholds are measured for three ranges of velocity in the HEVE. The experimental setup and procedure of two experiments are described, and the results are presented and discussed.

Chapter 4 studies the effects the base force intensity and the force increment or decrement on the force JND, the effects of the applied forces on the subject performance in an HEVE, and the adaptation of the subject's kinesthetic sense to forces in an HEVE. Three experiments are conducted for three levels of base force intensity. The experimental setup and procedure of experiments are explained in detail, and the results are presented and discussed.

Finally, Chapter 5 summarizes the findings and gives concluding remarks and directions on future research.

Chapter 2

Background

2.1 Haptic Display of Virtual Environments

The word haptic is originally from the Greek *haptesthai* which means the science of feeling. This thesis utilizes specialized terminology common to haptic research and important terms that are briefly defined in [1, 25]. Srinivasan et al. [1] defined the human haptic system as the entire mechanical, sensory, motor and cognitive components of the body-brain system. In addition, Oakley et al. [25] presented some of the definitions shared in both psychology and computing literature (e.g., Lederman in [26]; Srinivasan in [1]). Our haptic sensation includes kinesthetic, cutaneous, and proprioception senses. Kinesthetic sense, which is the focus of this thesis, is the feeling of motion through the sensation originating in muscles, tendons, and joints. Cutaneous sense is the feeling of external objects through contact with skin, and proprioceptive is the sensory information about body positioning [25].

Haptic interfaces are divided into two main categories: force feedback and tactile. Force feedback interfaces are used to explore and modify remote/virtual objects in three physical dimensions in applications, including computer-aided de-

Figure 2.1: Computer-aided assembly using force feedback haptic devices [16].

sign [12, 13], computer-assisted surgery [27], and computer-aided assembly [17] as shown in Figure 2.1. Tactile interfaces deal with surface properties such as roughness, smoothness, and temperature. This thesis focuses specifically on force feedback interfaces.

The motion of a user's hand is important in a variety of force feedback applications [28, 29, 30]. A user can slide on a virtual surface that has different haptic textures [29] or move in a simulated haptic fluid media in a virtual painting application [28]. When a user is immersed in a high-viscosity virtual media, the haptic display generates resistive forces that are proportional to the velocity of the user's hand motion [28]. Another application of motion is the haptic rendering of deformable objects. In this type of application, a user can penetrate into the object. Forces are applied both in and against the direction of the user's motion in a deformable object [31]. In all these applications, unlike previous research, the motion of a user's hand and that of the virtual haptic object is important. It is therefore essential to calculate appropriate force intensities based on both the property of the virtual material and the user's hand motion.

In the case of the virtual surface, force feedback interfaces should enable the user to distinguish between two different surfaces' frictions. To feel the friction of a virtual surface, a certain amount of force is applied to the user's hand via the haptic device when the user's hand touches one part of the surface. Furthermore, when the user's hand moves to a neighbouring part with a different friction, the applied force should be increased/decreased based on the friction of that part [31]. Therefore, *force increments* or *decrements* are frequently required in the haptic display of VEs.

Another important factor is whether the force is applied in the same direction or in opposition to the user's hand motion. To augment the teaching of standard physics concepts, several activities were developed by Williams et al. [29]. One activity allowed a user to feel different levels of sliding friction such as coarse, medium, and fine. In the haptic display of sliding friction, forces can be applied in opposition to the direction of movement. However, it is required to apply forces in the same direction as the user's hand movement in various applications. Lawrence et al. [32] applied forces in the same direction as the user's hand motion to compensate for the friction of a haptic device. Thus, *force direction* relative to the direction of the user's hand motion is critical in HEVEs.

Similar to other human computer interaction (HCI) systems, haptic-enabled VR systems require interactions between the human user and the computer. Several human-factors issues need to be investigated to ensure the effectiveness of these systems. The results of human factors studies can improve the design of usable and effective haptic interfaces [19]. For instance, users cannot perceive weak forces below a certain threshold due to the limitations of human force sensitivity. To ensure that users effectively perceive the force feedback in HEVEs, haptic displays should be able to apply forces greater than the threshold of human force perception [33]. Therefore, it is essential to measure the force threshold of human force perception, which is explained in Section 2.2.1.

Researchers have addressed the human factors in VEs as surveyed by Stanny et al. [19] who organized the research into three primary subtopics: human performance in virtual worlds, health and safety issues, and potential social implications of VEs. This thesis focuses only on the limitations of human force perception and the human performance in HEVEs, which will be addressed in the following section.

2.1.1 Human Performance in HEVEs

User performance is critical in VEs. A VE is effective only if a user can efficiently perform required tasks. Therefore, the main goal is to maximize the human performance in VEs. Much research has been conducted on factors that can affect the human performance in VEs [12, 21, 25, 27, 34, 35, 36]. Stanney et al. [19] surveyed three important factors: the navigational complexity, the degree of presence provided by VEs, and the users' performance on benchmark tests. The results of their survey show that the human performance increases by increasing the degree of presence and decreases by increasing the navigational complexity.

Navigation is important in the study of complex tasks in real and virtual environments. Navigation is divided into two main components: motor and cognitive [37]. The motor component is specified by a set of movements, from one location to a target location, and characterizes the position, orientation, and velocity of the motion. Darken and Sibert [38] classified navigation into three tasks: exploration, prime search, and naive search. In an exploration task, there is no target. In a prime search, there is a target, and the user knows the position of the target. In a naive search, there is a target, but the user does not know the location of the target. This thesis focuses only on prime and naive search tasks because user performance is analyzed in a target acquisition task in an HEVE. The cognitive component or wayfinding is the cognitive process of trajectory planning, which is not a focus of this study.

To evaluate the effectiveness of VEs, the measures of human performance are required. Researchers have generally analyzed user task performance with various criteria such as accuracy [20], binary failure/completion [39], and completion time [40].

The accuracy of movement is one of the most important measures in the study of user performance. Fitts [24] developed a task to systematically analyze the relationship between accuracy and speed. He proposed a model for human motor control behaviour based on the results of his experiments. His model is a descriptive model that provides a descriptive measure of human motor performance. Researchers have found the Fitts' model to be a valid motor control model to study human motor control in the applications where the user and the object are in relative motion [2]. The details of the Fitts' task and model are presented in Section 2.1.1.

Until quite recently, users tried to control their movement and accuracy with only visual cues in a virtual target acquisition task [41]. Several studies have also found that haptic feedback can improve user performance in VEs [12, 21, 25, 27, 34, 35, 36]. Oakley et al. [25] investigated the effects of adding force feedback to conventional computer interaction systems. They used force feedback to overcome interaction design challenges such as creating more realistic medical training simulations and augmenting conventional computer user interface. They found that force feedback improved accuracy in target acquisition and reduced the user's cognitive load on their visual and auditory senses.

Similarly, McGee [21] investigated the effects of adding force feedback to conventional graphical user interfaces. As shown in Figure 2.2, she designed a haptic-enabled scroll bar in a search task to reduce the amount of visual attention required by the user when scrolling through a document so the user focus on the

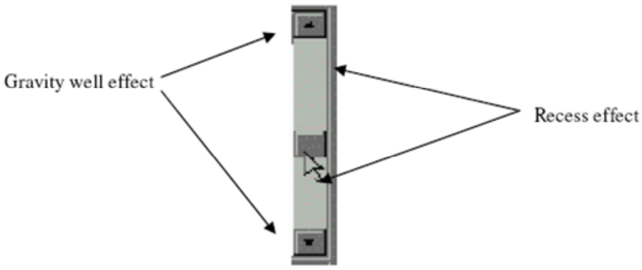


Figure 2.2: A haptic-enabled scroll bar [21].

reading/searching task. Errors in performing the scrolling task usually come from slipping as the pointer slips off the desired scrolling button, causing the user to miss the scroll. She utilized the concept of the gravity well from physics which emulates the gravitational potential field around a body. Virtual gravity wells were added to the up and down buttons of the scroll bar. The gravity well, a 0.5 N force, forced the user's hand to stay on the centre of the button, and prevented the user from accidentally slipping off the button when the cursor was over the button. The results show that the accuracy of movement is improved. The user's perception of workload is decreased.

The degree of presence of the user is also important in applications such as McGee's scroll bar where haptic devices pull or push a user's hand to maintain the accuracy of the task. What the user feels must be similar to what the user might feel in a real world situation. The experience would not be realistic if the user perceived the haptic device pushing or pulling him/her during a task.

Researchers have also found that the degree of presence can influence human performance in VEs [35, 42, 43, 44]. A high degree of presence is required for a VE to be effective and well-received by the user. This idea was supported by Sallnas et al. [35] in a study of interaction in a collaborative VE where visual, audio, and haptic feedback were provided. In their experimental setup, two users at different locations simultaneously felt and manipulated dynamic objects in the VE. The results have demonstrated that the force feedback significantly enhanced perceived virtual presence, task performance, and perceived task performance in the VE.

In order to achieve a high degree of presence, users should not feel resistance to their movements when there is not any interaction with virtual objects. In other words, a haptic device should not exert forces on the user's hand when the user's hand is in free motion. However, due to hardware limitations of haptic devices, haptic displays exert resistive forces to the user's hand motion, even if there is no contact with virtual objects. The resistive forces are generated by the friction and inertia in the motors and transmissions. The friction force is characterized by backdrive friction, and this force (N) indicates the magnitude of resistive force on the user's hand when the user's hand is in free motion. For instance, the backdrive friction of the PHANToM Omni is 0.26 N, which is reported in its manual as a design specification. Friction compensation methods have been developed to reduce the effect of the friction on the degree of presence [32, 45, 46]. For example, Lawrence et al. [32] designed a haptic interface with the aid of a friction-reducing controller to compensate for the friction. The user felt the residual effects when the friction was under-compensated. Conversely, the user felt an unnatural pulling when the friction was over-compensated. Thus, they measured the threshold of human force perception, and applied forces below the threshold so that the user would not be able to detect the friction compensation.

Researchers have also studied other possible factors that impact human performance in VEs [42, 47, 48]. Stanney et al. [19] organized a comprehensive set of these factors, including design constraints imposed by human sensory perception, user characteristics, task characteristics, integration issues with multimodal interactions, and the potential need for new visual, auditory and haptic design metaphors uniquely suited to virtual environments. This thesis focuses on the effects of sensory perception as they relate to the design of HEVEs.

To ensure that VEs are compatible with users, it is essential to know the abilities and limitations of human perception. In other words, VE designers need knowledge about human perception to obtain an understanding of design constraints influenced by sensory perception. Specifically, haptic perceptual issues can affect the design of VEs. For example, for the force feedback to be effectively perceived by users in HEVEs, the applied forces should exceed the threshold of force perception. Therefore, the threshold of force perception plays an important role in the creation of HEVEs [33].

The *difference threshold* or just noticeable difference (JND) is the minimum difference that we can notice between two stimuli: the base stimulus and an increment/decrement of the base stimulus [23]. The JNDs in the direction of stimuli increment and decrement are called *upper limen* and *lower limen* of the threshold [23]. Section 2.2 presents the required information about human perception and psychophysics.

In the physical world, psychophysical methods are employed to measure the force thresholds of the human haptic system for different test conditions, body sites, and base forces [49, 50, 51]. In HEVEs, we also need to know the impacts of emerging haptic technology on force perception. Therefore, psychophysical studies are required to find the force thresholds in HEVEs. Force thresholds have been measured in VEs with users in static interaction with virtual rigid objects [47, 48]. However, to my best knowledge, the force JNDs of small base forces, when the user's hand is in motion, have not been measured in HEVEs, even though a significant variation in force perception is observed when the velocity of the subject's hand is changed [52].

Adaptation to force is another important human factor in the haptic display of VEs. Sensory adaptation deals with a change in the responsiveness of the human sensory system over time to a constant stimulus [53]. In real world applications, users rely on cutaneous and kinesthetic senses to feel the texture and friction of a surface [52]. However, using force feedback devices, users generally use their kinesthetic sense to feel a virtual surface. Therefore, the adaptation of our kinesthetic sense in VEs should be studied to improve the haptic rendering of VEs.

Fitts' Law

Fitts [24] developed a task to systematically analyze the relationship between accuracy and speed. As shown in Figure 2.3, subjects were asked to tap a pencil-shaped object alternately on two rectangular plates by moving their hands left and right as rapidly as possible for a predetermined time. The width of the targets (W) and the amplitude of the movement between the targets (A) could be changed by the experimenter to generate a large number of combinations of W and A. Each time a subject tapped one of the targets, a hit was scored. Subjects were asked to score as many hits as they could. Four error plates were also mounted on both sides of each of the target plates. If subjects tapped any of the error plates, an error or miss was recorded. An *undershoot* error occurred when subjects tapped either of the interior error plates. An *overshoot* error occurred when subjects tapped either of the exterior error plates. Subjects were asked to limit misses to no more than 5%. In other words, subjects had to emphasize accuracy rather than speed.

Fitts presented a model of human motor behaviour. His model is a descriptive model that provides a descriptive measure of human motor performance or *throughput* known as Index of Performance: IP. His model is also a predictive model that provides a prediction equation to determine needed time to acquire a target, given the distance and size of the target [2]. The Fitts' model is given by

$$MT = a + bID \tag{2.1}$$

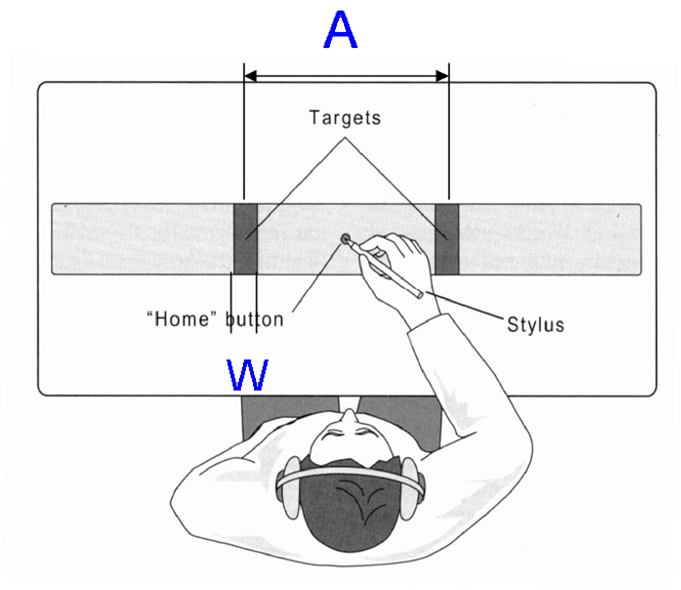


Figure 2.3: The original experimental setup of Fitts tapping task [54].

where MT is the resulting average movement time, a and b are the empirical constants of a linear equation, and ID represents the degree of difficulty of the task where:

$$ID = \log_2(\frac{2A}{W}) \tag{2.2}$$

such that A is the distance (Amplitude of Movement), and W is the width of the targets.

The Index of Performance (IP) is defined as

$$IP = \frac{ID}{MT} \tag{2.3}$$

and is the ratio of the index of difficulty to the average movement time.

Fitts conducted a series of experiments with different IDs (from 1 to 7). As presented in Section 2.2, the larger the distance, the more difficult the task; the larger the width, the easier the task. MT was calculated as the trial duration divided by the number of taps in that time (s/tap). Fitts suggested that, for a particular test condition, the Index of Performance should be relatively constant over a wide range of task difficulties. In other words, the ID-MT relationship is linear. In addition to IP, the accuracy of a subject in completing the assigned task is represented by the missing error (ME), which is the sum of overshoots and undershoots divided by the sum of hits, overshoots, and undershoots [24].

Researchers have used the Fitts' task to study the impact of haptic feedback in VEs [34, 36]. Wall and Harwin [36] studied the quantitative effects of haptics on user performance. They used the Fitts' law in conjunction with another task to develop a measure of human performance in a target task. They found that applied forces can improve the movement times for a difficult task, but had no effect on the index of performance (IP) as defined by the Fitts' law. In addition, a significant improvement in IP was found by adding haptic effects to a less difficult task (ID < 3).

Fitts' law was also used by Lee and Hannaford [34] who analyzed the effect of small forces on human performance, which can be useful for adding haptic interfaces to smaller systems such as laptops, PDA's, and even cell phones. They examined the weakest effects that can provide meaningful information to the user. They determined the lowest detectable forces rendered in the horizontal plane by a low-power, low-friction, and high-precision haptic device. The results have shown that small performance improvements of 0.1 bits/s at force feedback as low as 0.05 N.

The focus of this thesis is on motor control applications where the user and the object are in relative motion. In these applications, it is difficult to generate precise mathematical descriptions of behaviour. Therefore, an appropriate motor control task or law is required to study human motor control behaviour. The Fitts' task is used in this study because it represents a fundamental relationship that governs many kinds of motor behaviour [2].

2.1.2 Perception-based Haptic Compression Techniques

Currently, compression techniques play a significant role in transmission of multimedia information. If haptic data is to be stored, transmitted and reproduced, the efficient use of the available bandwidth and computational resources is a concern. Thus, haptic data compression and the evaluation of the perceptual impact of lossy compression of haptic data is a subject of recent studies [9, 10, 55, 56, 57].

The haptic data compression techniques are divided into two main categories: statistical [58] and perception-based approaches [55]. Statistical approaches mostly focus on the properties of the haptic signal. In contrast to the statistical approaches, perception-based approaches decrease the number of packets using a distortion metric based on the limitations of the human haptic system.

Ortega and Liu in Chapter 6 of *Touch in Virtual Environments* [59] proposed a statistical method that employed similar approaches to those used in speech coding to analyze haptic data. This approach is unlike the perception-based approach in this thesis. They developed compression techniques that are more specific to the haptic data, including a low-delay coding scheme based on differential pulse code modulation (DPCM). They also presented an alternative coding approach that uses the knowledge of the underlying graphical model. Their findings show that they achieve a compression rate of a factor of 10 using the Low-Delay Predictive coding compression technique.

A variety of statistical methods were compared by Shahabi et al. [58]. They presented and evaluated alternative techniques for achieving efficient sampling and compression of haptic data such as the movement, rotation, and force associated with user-directed objects in a VE. They experimentally determined the benefits and limitations of various techniques in terms of the data storage, bandwidth and accuracy. Again, their study does not include perception-based approaches. However, they summarized the result of the statistical approaches that might be useful to compare with the perception-based ones.

Hinterseer et al. [9] proposed a method to decrease the number of packets transmitted in a telepresence and teleaction system. They sent only haptic data over the network when the value of sampled sensor data is greater than a threshold value. The threshold value was determined in a psychophysical experiment. The results show a considerable reduction – of up to 90% in the packet rate and data rate – without any perceiveable effect on the fidelity and immersiveness of the telepresence system. Later, they extended their psychophysically motivated transmission method for multidimensional haptic data [10]. They used an example of a three dimensional haptic interaction that haptic data are only generated and transmitted if the change in haptic variables exceeds the JND of the human operator. Similar to their previous work, the approach reduces packet rates by up to 90% without impairing immersiveness.

Hinterseer et al. [11] also presented a model-based prediction of haptic data signals that can be used as a haptic compression technique. This technique can be used to compress haptic data in Internet-based multimedia applications such as haptic-supported games and the haptic rendering of VEs. This method works on the basis of the psychophysical properties of human perception. A two-user tele-operation system was set up, including an operator side and a tele-operator side. A signal prediction model was used on both sides that enabled the users to send packets over the network if the current actual signal differs from the predicted signal by a force threshold. The method reduced the packet rate by up to 95% without impairing immersiveness. Later, Hinterseer et al. [56] used fast Kalman filters on the input signals combined with model-based prediction of haptic signals.

Stability is one of the main issues in haptic systems. Instability might cause an undesirable feeling to the user and unrealistic interaction with the virtual environment. One of the most important approaches for designing a stable haptic display is the passivity-based (energy-based) approach. The extracted energy from the virtual environment can cause unrealistic feelings with severe destabilizing effects. Colgate et al. [60] have used a passivity-based model to design stable haptic displays. Kuschel et al. [57] addressed the issue of stability in data compression algorithms that discard unnoticed data. They focused on guaranteed stability or passivity of a system that uses a lossy data reduction (LDR) algorithm. They proposed a classification scheme for a class of LDR algorithms and derived sufficient stability conditions.

Knowledge about the threshold of human force perception is essential in all reviewed perception-based compression techniques. It is thus necessary to investigate the impact of important factors on the force threshold, including the force direction, base force intensity, force increment/decrement, adaptation, and velocity of the user's hand. However, the effects of these factors have not been addressed in the literature. This thesis studies a comprehensive set of these factors when the user's hand is in motion.

2.2 Sensation, Perception and Psychophysics

In everyday life, we use our senses to interact with the environment. We can see, touch, smell, hear and taste the external world surrounding us through interactions that usually occur with an initial contact between an organism and its environment. Sensation mostly deals with the initial processes of detecting and encoding environmental energy during the interactions. Essentially, our sense organs convert the energy signals from the environment to bioelectric neural codes and send the codes to the brain [61]. The cell receptors of the eye receive the light as environmental energy, transform it into bioelectric codes and then transmit the codes to the brain.

Sensation not only deals with the study of the biological events such as the reaction of the eye cells to light energy, but also concerns the relation of sensory experiences to the functioning of sense organs.

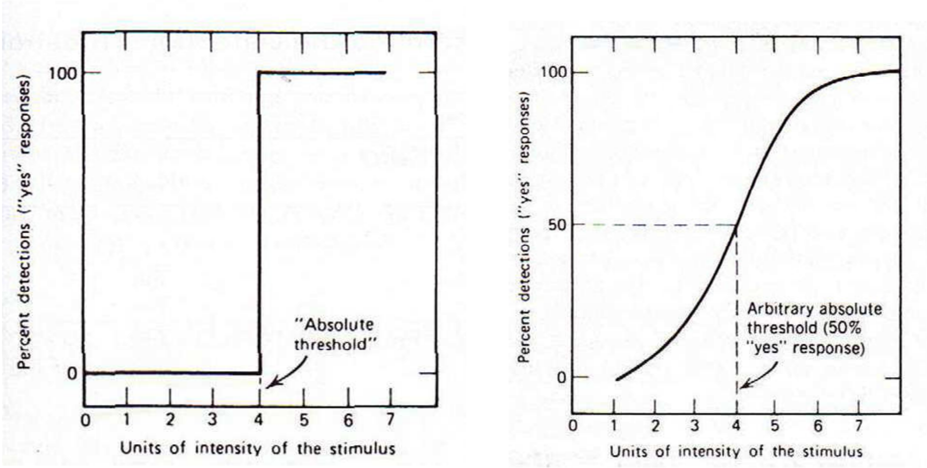
In addition to sensations, psychological processes are also required to give meaning to the bioelectric neural codes. When we watch television, our eye initially detects a series of images. However, psychological processes enable us to perceive concepts from the images based on our past experiences, memory, or judgement. In other words, psychological processes present the visual events in a meaningful way. Perception deals with these psychological processes that are required to organize, interpret and give meaning to the output of sense organs. Thus, the main objective of sensation and perception is to obtain accurate and reliable information about the environment [61].

The kinesthetic sense is often used to help manipulate objects in the real life among other movement's tasks. The kinesthetic sense is not as well understood as the cutaneous sense, despite the fact that people maintain their normal and coordinated behaviour using vital information from their kinesthetic sense. This is due to the fact that differentiating the cutaneous sense from the kinesthetic sense is a difficult task, making it difficult to develop a direct study about the kinesthetic sense. The human haptic system also contains the motor system and a cognitive system in addition to the kinesthetic system. People use the motor system to manipulate objects, and the cognitive system to connect sensations to perception and action. Thus, all the aforementioned systems are taken into account when investigating force feedback interactions.

Psychophysics refers to the methodology of studying perception. The methodologies from psychophysics are used to study perception [23]. Psychophysical methods enable us to establish a relation between certain features of environmental stimulation and sensory experiences. *Detection* and *discrimination* are the most important perceptual problems that have been addressed in psychophysics. These problems involve the measurement of sensory thresholds, or the perceptual limits of the human sense organs [62]. This thesis measured the sensory thresholds of human force perception in an HEVE.

2.2.1 Sensory Thresholds

Detection aims to determine if a stimulus is present or not. Detection relates to the absolute sensitivity of our perception and involves determining the absolute threshold of perception. The absolute threshold is defined as the "smallest amount of stimulus energy necessary to produce a sensation" [23]. It can theoretically be assumed that the absolute threshold is a precise magnitude or stimulus point on the intensity when an observer detects the stimulus and responds *yes*. As shown in Figure 2.4a, the observer cannot detect the stimulus if the intensity is less than 4 units, and a stimulus is detected 100% of the time if its intensity is equal or above 4 units. However, experimental results have shown that the relationship between the detection and intensity of a stimulus is not necessarily as fixed as it is in Figure 2.4a. Researchers have found that the relation is an S-shaped curve as depicted in Figure 2.4b [61]. The absolute threshold value is conventionally defined as the intensity of a stimulus that is detected on half of the test trials. Figure 2.4b shows a typical experimental function of the absolute threshold detection. The half of *yes* responses yields to 4 units. The discrimination problem involves deciding whether two stimuli are identical or not. In order to find if there is any difference between the two stimuli, the smallest difference between two stimuli should be measured. The difference threshold or just noticeable difference (JND) is a measure of the minimum difference between two stimuli that is necessary in order for the difference to be reliably perceived. The first stimulus is called *base* stimulus, and the second stimulus is an increment/decrement of the base stimuli. The JND in the



a) **b)**

Figure 2.4: a) The stimulus intensity relates to absolute threshold. b) The absolute threshold is the intensity that is detected on half of the trials [61].

direction of stimuli increment is called the upper limen, and the JND in the direction of stimuli decrement is called the lower limen [23]. In discrimination experiments, the focus is mostly on the difference in the intensity of two stimuli. However, other dimensions of variation, such as frequency, intensity level, or adaptation time, have also been investigated [23]. Intensity is subjective quantity which can be triggered by different attributes of a stimulus. This thesis focus on the amplitude of force as force intensity.

In 1834, Weber studied the relationship between the difference thresholds or JNDs and the intensity levels of the base stimulus. He discovered that the JND increases significantly for very small intensities and decreases while the intensity of the base stimulus increases. For relatively large base stimuli, Weber found that the JND is a linear function of stimulus intensity. In other words, the difference threshold is always a constant fraction of the stimulus intensity for those base stimuli; this fraction is called Weber's fraction. This trend, as shown in the top graph of Figure 2.5, is observed by other researchers and is called the Weber trend [23].

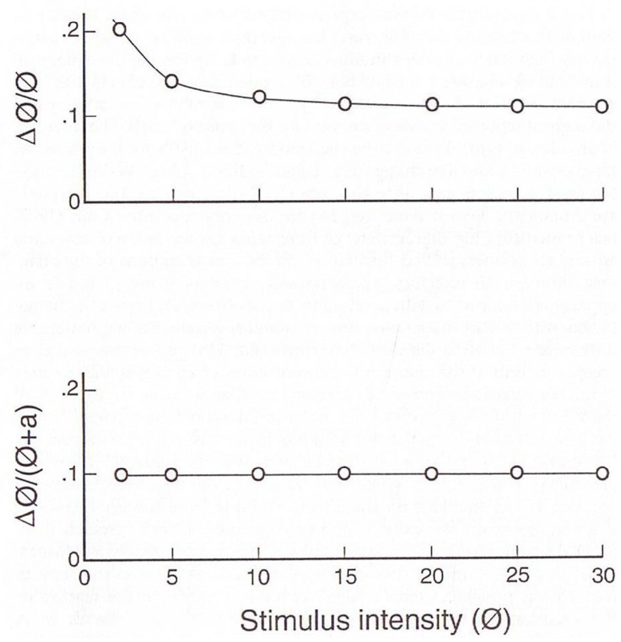


Figure 2.5: The Weber trend for hypothetical results is shown in the top graph in which $\Delta\phi/\phi$ increases significantly for very small stimulus intensity. The bottom graph shows the variation of Weber's law with the additive constant a [23].

The value of Weber's fraction is different for various senses.

The linear relationship is a valid law for all senses and sense organs. This relationship is called Weber's law, which can be represented as

$$\Delta\phi = c\phi \quad or \quad \Delta\phi/\phi = c, \tag{2.4}$$

where c is the constant Weber's fraction, $\Delta\phi$ is the change in the stimulus intensity that can just be noticeably different (JND), and ϕ is the starting intensity of the stimulus or base stimulus.

For extremely low intensities, a small constant offset, a, can be added to the base stimulus term to determine a better fit to the data as shown in Figure 2.5. Equation 2.5 is the modification of Weber's law with the small constant offset.

$$\Delta\phi = c(\phi + a) \quad or \quad \frac{\Delta\phi}{\phi + a} = c, \tag{2.5}$$

where c is the constant Weber's fraction, $\Delta\phi$ is the change in the stimulus intensity, ϕ is the base stimulus, and a is the constant offset.

Figure 2.5 shows the difference between Weber's law and its variation with the additive constant a. In the top graph, there is a significant deviation in $\Delta\phi/\phi$ at small values of ϕ. $\Delta\phi/\phi$ is approximately constant for the rest of ϕ values. However, as shown in bottom graph, $\Delta\phi/(\phi + a)$ is constant for all values of ϕ. In other words, Weber's law (Equation 2.5) explains the results over the entire range of ϕ values when a is added to ϕ values.

There is a situation in which the stimulus is too weak, and a reliable response is not produced. In other words, the intensity of stimulus is below the threshold of human perception. In this situation, the magnitude is called *sub-threshold* [61]. This thesis studies the effects of the sub-threshold forces on user performance in an HEVE.

2.2.2 The Force Thresholds of the Human Haptic System

Researchers have determined the force thresholds in real world situations [49, 50, 51]. Jones [49], in a force matching experiment focused on a human elbow, found a JND ranging between 5% and 9% over a range of different base force values. Subjects were required to generate forces ranging from 15 to 85% of their maximum voluntary contraction (169-482 N). Pang et al. [50] determined a JND that lies between 5% and 10% for pinching motions between finger and thumb with a constant resisting force. This JND was found to be relatively constant over a range of different base force values between 2.5 and 10 N. Raj et al. [51] studied the ability of human subjects to discriminate between different magnitudes of weights. They found JNDs of 12%-13% for large base weights (80-200 g) lifted by the middle finger about the metacarpophalangeal (MCP) joint.

Recently, Allin et al. [48] measured force JND in a VE. The goal was to use the force threshold to construct therapeutic force feedback distortions that stay below the threshold. The focus was on JND as applied to the index finger. The result was an average JND of approximately 10% over a number of subjects with a constant base force at 2.25 N. The conclusion was that the visual feedback distortions in a VE can be created to encourage the increment of force production by up to 10%, without a patient's awareness.

Doerrer et al. [63] conducted several experiments to measure the force threshold of the human finger on a push-button. A haptic display was used to simulate push-buttons with programmable force/displacement curves. During the experiment, the force JND and the absolute force threshold were determined when subjects pressed the push-button. On average, the subjects were able to perceive a sudden change of force if the change was larger than 0.1 N.

Force Thresholds and Motion

In the previous subsection, the reviewed studies have measured the force thresholds in the haptic display of stationary rigid objects, which interact with the operator's hand. However, motion is critical in many VR applications, as detailed in Section 2.1.

Very little research has considered the study of motion and perception in the haptic displays [52, 64]. Lederman et al. [52] investigated the effects of the speed of the relative motion on perceived roughness via a rigid probe. Several experiments were conducted based on the mode of touch, active or passive, and different ranges of velocities. It was realized that the effects are multiple and complex. The results show that increasing speed tended to render surfaces as smoother. It was also observed that the inter-element spacing for texture perception has a significant effect in addition to changes in the speed. In other words, perceived roughness decreases with increasing speed, up to the point where the probe tip is able to fall between the inter-element spaces, where the effect is reversed. This thesis also focuses on the effects of the relative velocity on the human haptic perception. However, the goal is to explore the limitations of the haptic perception in the haptic rendering of VEs.

Jandura and Srinivasan [64] conducted torque discrimination experiments for a slow twisting motion. Subjects were asked to maintain a constant angular velocity, while a constant torque was applied on the subjects' hands. The results show that the JND for torque was 12.7% when the reference torque was 60 mN-m.

2.2.3 Adaptation to Forces

Sensory adaptation deals with a change in the responsiveness of the human sensory system over time to a constant stimulus [53]. For example, we immediately feel the texture of an object's surface when we rest our hand on the object. However, after a few seconds we cease to feel the object's surface. In other words, our sensitivity lessens to a constant stimulus, and may also disappear after a while. Not only does the *duration* of exposure to the stimulus play a significant role, but the stimulus intensity is also important in the adaptation of our sensory system. The feeling of stronger stimuli will slowly decrease compared to weaker stimuli. We are also sensitive to a change in the stimulus, and the feeling can be restored by moving our hand on the surface of an object [61]. In other words, our sensory system can be re-sensitized by the movement of the hand on the object's surface.

In real world applications, users can feel the texture and friction of a surface via tactile and force feedback [52]. However, in VEs, users rely on their kinesthetic sense to feel a virtual surface using force feedback devices. Therefore, the adaptation of our kinesthetic sense in interaction with VEs must be studied to improve the haptic rendering of VEs. Essentially, if the users adapt to forces, they are less sensitive to changes in the applied forces. For instance, the compression techniques in Section 2.1.2 can more efficiently work on haptic data, and the sub-threshold forces can be increased as in the application of friction compensation [32].

Many studies have also focused on motor adaptation in reaching movements [65, 66, 67]. Unexpected force perturbations usually affect a smooth and straight trajectory of the user's hand in a 2D space. A robot manipulator is typically used to apply forces to the user. The forces usually alter the user's hand movement and decrease the user's accuracy. The user can compensate for the effect of the forces, if the forces do not change. The trajectories are back to the original straight-line path after a few trials. The user employs motor adaptation to anticipate or counteract the forces and maintain or restore the accuracy [67].

Coello et al. [65] showed that adaptation can occur without visual feedback. Dizio and Lackner [66] have investigated motor adaptation with congenitally blind subjects. They have shown the existence of motor adaptation to forces in a single-force environment. The results indicate that the proprioceptive sensing of the limb position plays a significant role in complete motor adaptation to forces.

Scheid et al. [67] have studied motor adaptation to perturbing forces, including the centrifugal and Coriolis forces in a multi-force environment. Their results show that motor adaptation is based on the integration of visual and proprioceptive information before the execution of a reaching movement. The results have confirmed the existence of distinct adaptive mechanisms reacting to the centrifugal and to the Coriolis forces.

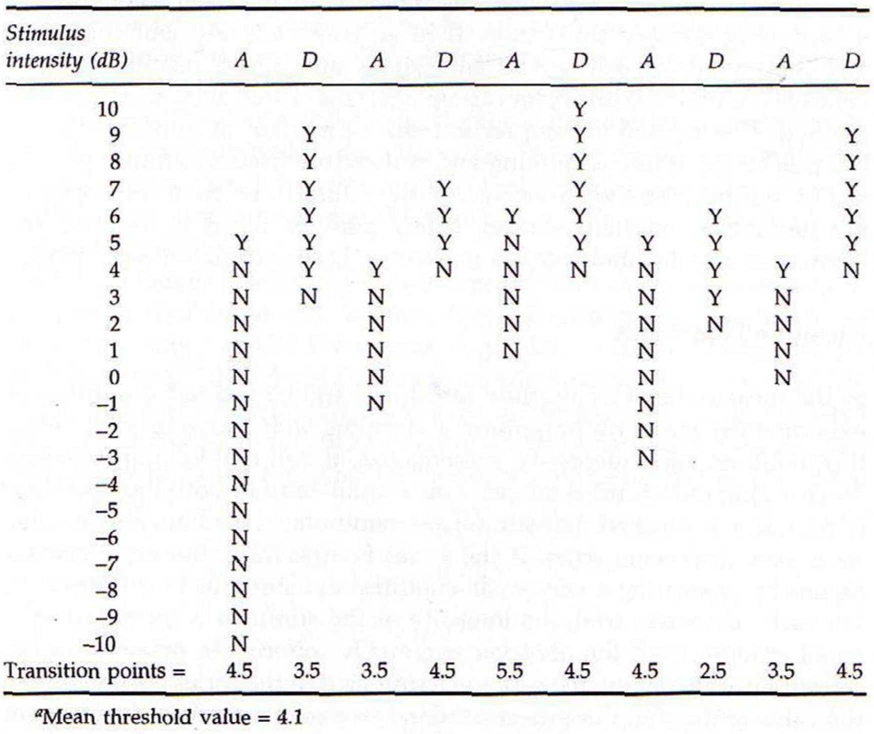
The focus of this thesis is also on adaptation to forces, but with regard to the adaptation of the kinesthetic sense, not proprioceptive position sense. This thesis investigates the adaptation to small forces that are near the force threshold of the human haptic system.

2.2.4 Psychophysical Methods for Measuring Thresholds

There are many methods to determine the absolute and difference thresholds. According to Gescheider [23], methods of limits, constant stimuli, and adjustment are among the most well known methods for detecting absolute and difference thresholds. People are usually presented with the same stimuli on different occasions. However, they do not always respond in the same ways. The main reason for this is presumably that the neurosensory system allows a margin of error. Other sources of biases such as learning and adaptation, can also be a factor.

Method of limits, Staircase and Interweaving Staircase Methods

One of the best techniques for detecting sensory thresholds is the method of limits and it is not as time consuming as other methods. Figure 2.6 shows the results where a subject is presented with a stimulus well above or below the expected threshold. On each trial, the subject indicates detection of the stimulus with a *yes* response, or non-detection with a *no*. The experimenter increments the stimulus on successive trials if the first stimulus presented is below the threshold, until the subject changes his response from *no* to *yes*. If the first stimulus is over threshold, the stimuli are gradually decremented in steps until the subject's response changes from *yes* to *no*. A series is terminated immediately after the first change in response, and the transition point for that series is taken as the stimulus value halfway between the last two stimulus values. Several ascending and descending series can be conducted, and the absolute threshold is the average of the transition points over all of the



Stimulus intensity (dB)	*A*	*D*	*A*	*D*	*A*	*D*	*A*	*D*	*A*	*D*
10						Y				
9		Y				Y				Y
8		Y				Y				Y
7		Y		Y		Y				Y
6		Y		Y	Y	Y		Y		Y
5	Y	Y		Y	N	Y	Y	Y		Y
4	N	Y	Y	N	N	N	N	Y	Y	N
3	N	N	N		N		N	Y	N	
2	N		N		N		N	N	N	
1	N		N		N		N		N	
0	N		N				N		N	
–1	N		N				N			
–2	N						N			
–3	N						N			
–4	N									
–5	N									
–6	N									
–7	N									
–8	N									
–9	N									
–10	N									
Transition points =	4.5	3.5	3.5	4.5	5.5	4.5	4.5	2.5	3.5	4.5

[a]Mean threshold value = 4.1

Figure 2.6: Method of limits: the alternate ascending (A) and descending (D) series are shown. Transition points and their mean value (the threshold) are indicated at the bottom [23].

series.

A number of errors can occur during the method of limits. The sources of response bias are habituation and expectation. An observer might tend to develop a habit of repeating the same response because the stimulus gradually changed in the direction of threshold over several trials. This habit might influence the result as a constant error, and this type of error is called the error of habituation. Conversely, sometimes observers might falsely expect the arrival of the stimulus at their threshold, and keep reporting that the change has happened. This is referred to as the error of expectation. Errors of habituation and expectation may cancel each other if they have the same magnitude. Averaging over many series, and alternating between ascending and descending series, also helps to compensate for some of the errors of habituation and expectation. Varying the starting point for successive series is another solution reducing the error of expectation. Another useful technique is to avoid the use of excessively long trial series to reduce the errors of habituation.

Another effective method is the *staircase method* which is a modification of method of limits for detecting absolute thresholds. It is very similar to the method of limits with the only difference being that each series does not terminate after a transition point, and the direction of the series is reversed. As shown in Figure 2.7, if the stimulus is being incremented, after the first *yes* response it will begin to be decremented, and vice versa. The procedure is finished when a sufficient number of response transition points have been recorded. The result of averaging the transition points is the threshold. This method takes less time compared to other methods because only a few stimulus values that are far above or below threshold are presented. Although it is a very efficient method, its sources of biases are the same as the method of limits [23].

The Interweaving Staircase (IS) [68] method is a variation of the staircase

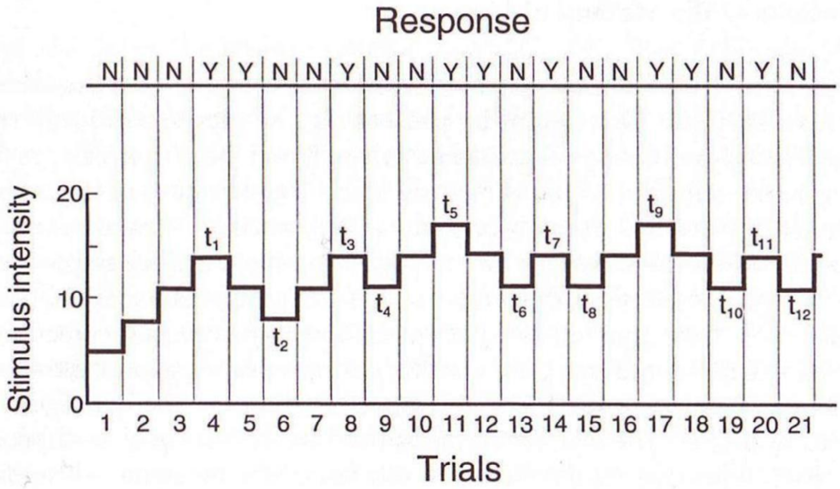


Figure 2.7: Staircase method: *yes* (Y) or *no* (N) responses are shown in the top of figure. The transition points are indicated above and below of stairs [23].

method that is used to measure the JND in the direction of force increment and in the direction of force decrement. In the IS method, the experimenter starts by presenting a sequence of forces which is the base force plus the increment or decrement, then progressively increases or decreases in value. The subject responds with *yes* to increment or decrement or *no* to detecting changes in force value. When the subject's response changes from one or a series of the same response to the other response, as is the case of *yes, yes, yes* switching to *no*, the force value is recorded, and the direction of the force sequence is reversed from ascending to descending, or vice versa. These points are called transition points. The transition points are recorded and the JND value is the average value of the transition points.

The main advantage of the IS method is to reduce the possible biases compared to the original staircase method. In the IS method, a subject has to report one of the three possible responses, *increment*, *decrement*, or *no change*. Therefore, it is much more difficult for the subject to guess the response, and it is possible for the experimenter to check the response with the current direction of force whether ascending or descending.

Method of adjustment

The method of adjustment is used for determining difference and absolute thresholds. Unlike the previous methods, participants are actively involved in the method of adjustment [23]. Participants directly control a variable stimulus intensity, which helps participants to concentrate on the experiment and thus decreases the number of errors. To obtain the threshold, the experimenter sets the stimulus value well above or below threshold. Then the participants decrease the stimulus intensity until they cannot detect the stimuli, or increase the stimulus until they can detect it for the first time. The absolute threshold is taken to be the final settings from all trials.

Method of constant stimuli

The same stimulus is presented to participants many times in the method of constant stimuli. A range of different stimulus values are used between those that are almost never detected to those that are almost always detected. On each trial, the participants respond by *yes* or *no* to indicate that they detected the stimulus or not. As shown in Figure 2.8, an S-shaped curve has been fitted to the points of a threshold measurement, and it is called a psychometric function [23]. The stimulus intensity at which the proportion of *yes* responses is 50% is taken to be the absolute threshold of detection.

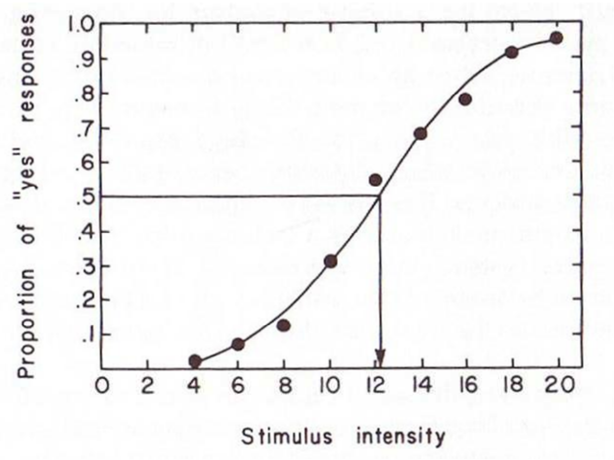


Figure 2.8: An S-shaped curve in the measurement of threshold using the method of constant stimuli, leading to construct a typical psychometric function [23].

Chapter 3

The Effect of Velocity on Force Perception in HEVEs

3.1 Introduction

This chapter reports the results of a pilot study that was conducted to investigate the relation between motion and human haptic perception. We study the effects of a user's hand velocity on force perception in an HEVE. The focus is on the determination of difference force threshold or JND by measuring the upper and lower limens of force JND. The force JND is obtained in the free motion condition of the PHANToM device when the device end-effector is grasped by a subject's hand. In free motion, there is no interaction with virtual objects, and no force feedback is applied on the subject's hand. The only force on the user's hand is a resistive force due to the backdrive friction of the device. Thus, this friction force is the base force for the force JND when no force feedback is applied. In the next chapter, a full study is conducted to measure force JNDs for three base forces when force feedback is also applied on the subject's hand.

In this chapter, in two experiments, subjects are asked to report the just noticeable difference between this base force and an increment/decrement from it when they perceive the JND. The upper and lower limens of the force JND are quantified for three ranges of velocity: low (0.03 - 0.05 m/s), medium (0.12 - 0.15 m/s), and high (0.22 - 0.28 m/s). The experiments of this chapter are presented in Section 3.3, and the details of the full study are described in the next chapter.

The hypothesis is presented in the next section, and the experiments are described in detail in Section 3.3. The upper and lower limens of force JND for the three ranges of velocity are presented in Section 3.4, and discussed in Section 3.5.

3.2 Hypothesis

In this section, the main hypothesis is presented.

H_1**:** The force JND of human force perception increases when the velocity of user's hand increases in an HEVE.

3.3 Methods

This section describes the two conducted experiments, which use the same setup, task, and procedure. The direction of applied forces is the only difference between the two experiments. In the first experiment, the applied force is in the same direction of hand motion (aid force). Thus, the force partially cancels the friction, and decreases the resistive force. In the second experiment, the applied force is in opposition to the direction of the subject's hand motion (opposed force) and increases the resistive force.

3.3.1 Participants

There were eight participants who were between the ages of 27 and 34. All were regular computer users and students at the University of Waterloo. Participation was voluntary. They were right-handed, and had no more than trivial previous exposure to haptic interfaces. The participants did not have any neurological illness or physical injury that would impair hand function or force control ability. The experiment was conducted in accordance with the University of Waterloo ethical guidelines. Consent letters were obtained from all participants. The office of research at the University of Waterloo approved these experiments as Research Involving Human Participants (ORE #: 12738).

3.3.2 Apparatus

The PHANToM^{TM} Omni device made by SensAble Technologies Inc. [69], shown in Figure 3.1, was used in both experiments. This haptic device has been designed for a vast variety of applications, including medical, scientific and industrial [69]. In general, some of the advantages of PHANToM device are their 3D force-feedback, the ability to operate in an office or desktop environment, compatibility with standard PCs and useful for a broad range of applications.

PHANToM Omni haptic devices have a relatively large workspace for desktop applications, suitable for a large range of hand motions, stiffnesses and motor forces to meet the specific requirements of this research project. Comparing to other haptic devices, this device is widely used in various applications because of its reasonable price. This device can generate maximum 3.3 N force [69], which is enough for the purpose of the experiments in this thesis. The applied forces in the experiments in this and the next chapters are less than 1 N. Another important characteristic of the device is the backdrive friction, which is reported as up to 0.26

Figure 3.1: The PHANToM^{TM} Omni device made by SensAble Technologies Inc. [69].

N [69]. In Section 3.3.2, this friction and its variability are estimated for the part of work space that is used in the experiments. Essentially, the variability is important because we need to know the minimum detectable force output of the device.

The haptic device is connected to a personal computer through a Firewire interface card. The software has two processes, haptic and graphic, that are run on two 3GHz Pentium 4 computers running Windows XP. Force feedback is generated by the haptic process that is developed in MATLAB using the proSENSE toolbox [70]. The graphic process renders a 2D VE that is shown in Figure 3.2. The 2D VE is created using V-Realm Builder [71] and graphically rendered using the MATLAB Virtual Reality Toolbox Viewer [72]. The VE contains a colour ball and a colour bar. The colour ball represents the position of the device end effector (grasped by the subject's hand). The bar is stationary and has two green ends (targets). The center-to-center distance between the targets on the bar is 10.2 cm. As shown in Figure 3.3, a 17" LCD monitor, which is placed approximately 70 cm from the subject, is used to display the VE. The update rate of haptic (force) display is 1000 Hz.

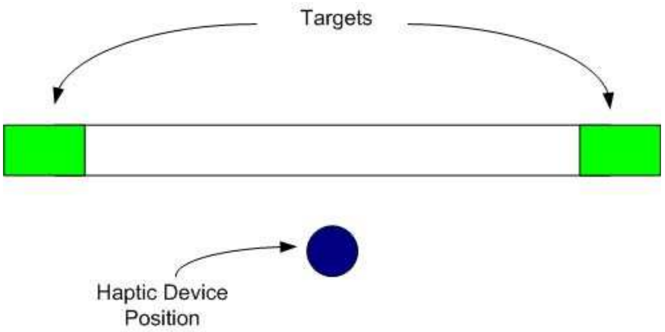


Figure 3.2: The 2D VE that contains a 2D ball and a bar with two green target zones.

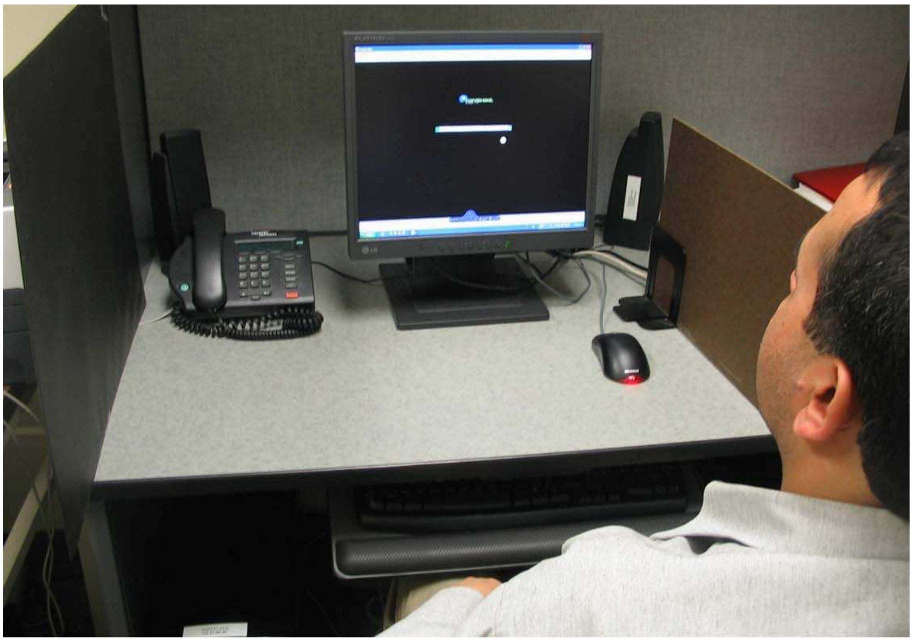


Figure 3.3: The computer display shows the 2D VE.

Estimation of the Device Friction

In the experiment, the base force is the resistive force due to the friction of the haptic device, which includes coulomb and viscous (damping) friction. Coulomb or dry friction is independent of velocity, however, viscous friction is proportional to the velocity of device end-effector [73], and is usually reported as a coefficient in Ns/m. Similar to coulomb friction, viscous friction is calculated in N when viscous damping coefficient is multiplied by velocity (m/s).

The viscous frictions of PHANToM devices are very small because a cable-pulley transmission is used in these devices. Diolait et al. [74] found that the coulomb friction is 0.038 N and the viscous friction coefficient is 0.005 N.s/m for PHANToM 1.0 haptic device. Thus, if the end-effector moves by 0.28 m/s, the viscous friction is 0.0014 N, which is negligible compared to the coulomb friction. Their measured friction is similar to the backdrive friction of the PHANToM 1.0, up to 0.04 N, as reported in the device specifications [69].

The backdrive friction of the PHANToM Omni is reported up to 0.26 N [69], which is 6.5 times larger than the friction of PHANToM 1.0. Therefore, the Omni viscous friction is approximately 0.009 N if the end-effector of Omni moves by 0.28 m/s, which is the maximum velocity in this thesis. Thus, in all experiments in this thesis, it is assumed that the resistive force is only due to the coulomb friction of the device, which is basically independent of velocity.

In addition, the preliminary experiments showed that the friction was variable within the workspace of the device. In other words, when we moved the device end-effector manually, we had to change the force intensity to maintain the motion with a constant velocity. Therefore, the friction and its variability were estimated within the part of workspace that was used in the experiments. The workspace was a 10.2 cm path, from -0.051 to 0.051 m on the x-axis of the device workspace.

In order to determine the friction, varying force profiles were applied to: a) move the end-effector from a static condition and b) keep an approximately constant velocity of the end-effector from the beginning to the end of the path. The applied force in b) should be equal to the friction if the force produces an equilibrium trajectory (the end-effector moves with a constant velocity on the whole path).

Initially, the end-effector was placed at a point (0.07 m on x-axis) before the beginning of the path. A relatively high intensity force was applied to the end-effector for 400 ms to move the end-effector toward the beginning of the path (0.051 m on x-axis). Finally, a weaker force was applied to the end-effector and this force was maintained until the device reached the end of the path.

Since the friction was variable, two frictions were estimated when the end-effector moved from right to left and left to right. To estimate the right to left friction, first, forces with different magnitudes were applied to find the force that could overcome the static friction. A 0.5 N force could initially move the end-effector, and overcome the static friction. Then, a weaker force of 0.26 N was applied to maintain a constant velocity (around 0.16 m/s). Figure 3.4 shows the trajectory of the end-effector when the force profile was applied. For the first 1000 ms, no force was applied, and then 0.5 N was applied for 400 ms followed by 0.26 N for 1600 ms.

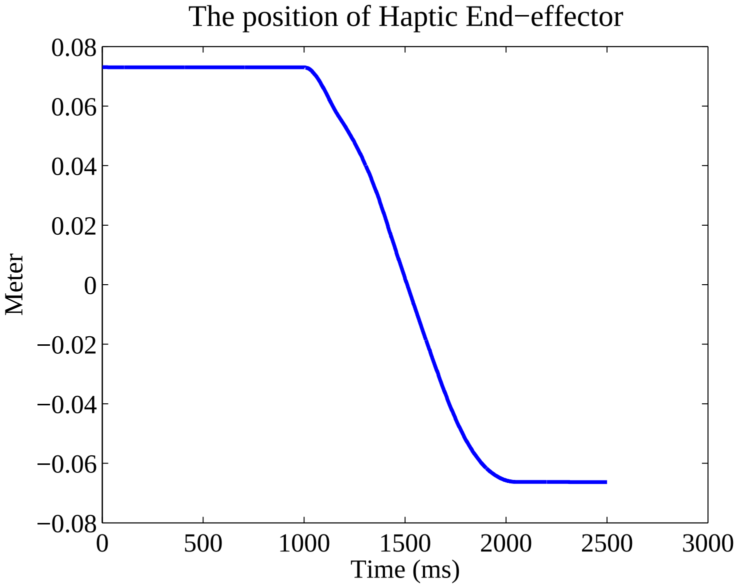


Figure 3.4: The end-effector trajectory when no force was applied for 1000 ms, then a 0.5 N force was applied for 400 ms followed by a 0.26 N for 1600 ms.

To estimate the left to right friction, the force to overcome the static friction was 0.31 N, which was less than the applied force for the right to left. However, the force applied to maintain a constant velocity was slightly higher at 0.28 N.

Based on the results, the friction was 0.27 ± 0.01 N, which was the average of the two weaker forces for the right to left and left to right movements.

Other researchers ignored the friction force in their base force because the friction force is negligible compared to large base forces applied by the actuators such as 2.25 N in Allin's work [48]. However, in this thesis, the small friction force should be taken into account because our base forces are small.

3.3.3 Design

In this pilot study, a mixed model design was used in the experiments [75]. This model involves both a within-subject design as well as a between-subject design. In the mixed model design, several independent variables can vary within subjects and other variables can vary between subjects. The conducted experiments were devised to measure the force JNDs in a velocity-based scenario. The dependent variable was the force JND of human force perception. The independent variables were the velocity of subject's hand motion and the force increment/decrement. All participants experienced all three levels of the velocity because the main goal is to investigate the effect of the velocity. However, four subjects experienced the force increment or the force decrement since four subjects were enough to determine one limen of force JND. Participants were divided into two groups of four. One female and three male subjects were in each group. The first group participated in the experiment for the force increment and the second group participated for the force decrement. The order of the experiments and levels randomly assigned to the subjects.

3.3.4 Procedure

Each subject is seated on a chair facing a computer display and asked to place their right elbow on a side support. The wrist of the right hand is restrained with a wrist guard, as shown in Figure 3.5, so that wrist movements are locked to ensure that subjects just rotate their hands about their elbows. The subject grasps the end-effector of the haptic device.

During each experiment, the attention of the subject is directed to the display containing the 2D VE, as shown in Figure 3.2. The ball represents the device end-effector and moves when the subject moves the end-effector. The right arm and

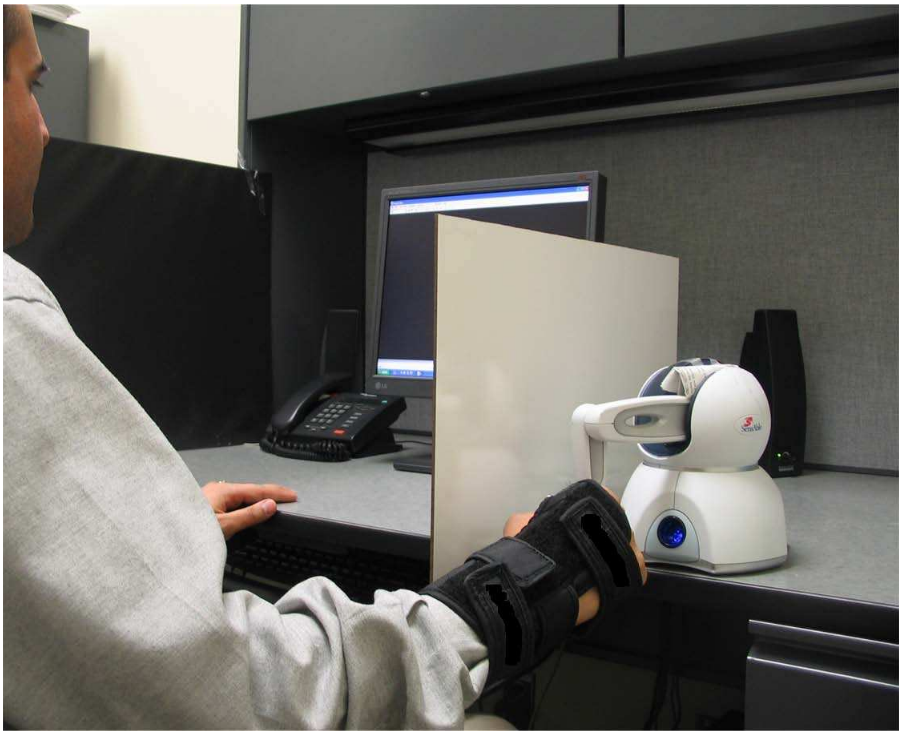


Figure 3.5: The subject grasps the end-effector of the PHANToM^{TM} Omni and rotate his hand about his elbow.

fingers of subjects are shielded from their own view with an opaque barrier to ensure subjects control their hands' movement via visual feedback from the display. The subject is asked to move his/her hand, back and forth, from left to right and then right to left, repeatedly. The subject is required to maintain the red ball between the green zones and not go beyond the zones.

Three ranges of reference velocity are selected based on two factors. First, the ability of subjects to carry out the experimental task at the velocity ranges. Second, having relatively large rooms among the ranges to study any potential significant difference of the force JNDs at the ranges. The selected ranges are low (0.03 - 0.05 m/s), medium (0.12 - 0.15 m/s), and high (0.22 - 0.28 m/s). To find the ranges at which subjects could complete the task, several subjects, other than the main eight subjects, carried out the task within various velocity ranges before starting the main experiments.

All subjects are required to maintain their hand velocity within the specified ranges in three different experiments. The colour of the ball in the display aids the subjects in maintaining the average value of their hands' velocity at the reference velocity. If the subject's velocity is within the range of reference velocity, the ball's colour is red. Otherwise its colour is yellow. Therefore, the subjects control their hands' velocity by observing the ball's colour. To ensure that subjects can control the velocity, they are given training before starting the main experiments.

The average velocity is used because the subject stops at the end of the bar and moves towards the other side of the bar in the 2D VE, as shown Figure 3.2. If the velocity at each instant in time is used, then the ball's colour would turn to yellow at the end of the bar, and the subject might inadvertently apply extra force. This can distract the subject and affect the process of measuring the force JNDs. Thus, the mean velocity value is used as it does not change rapidly when the subject stops at the end of the bar, and the ball's colour does not turn to yellow.

The staircase method, which is explained in Section 2.2.4, is used to measure the force JNDs in this chapter. In the middle of each trial, the experimenter applies a certain amount of either opposed or aid force to the subject's hand motion based on the staircase procedure. Each subject is asked to report any changes in the haptic sensations on their hand during each trial. Before applying the force, the experimenter ensures that each subject maintained the hand velocity within the reference range. The procedure is finished when 12 transition points are obtained. Therefore, the number of trials is variable. As a results, the duration of experiment is variable, and one experiment typically takes from 15 to 25 minutes. Twelve transition points are recorded and the force JND value is the average value of the transition points.

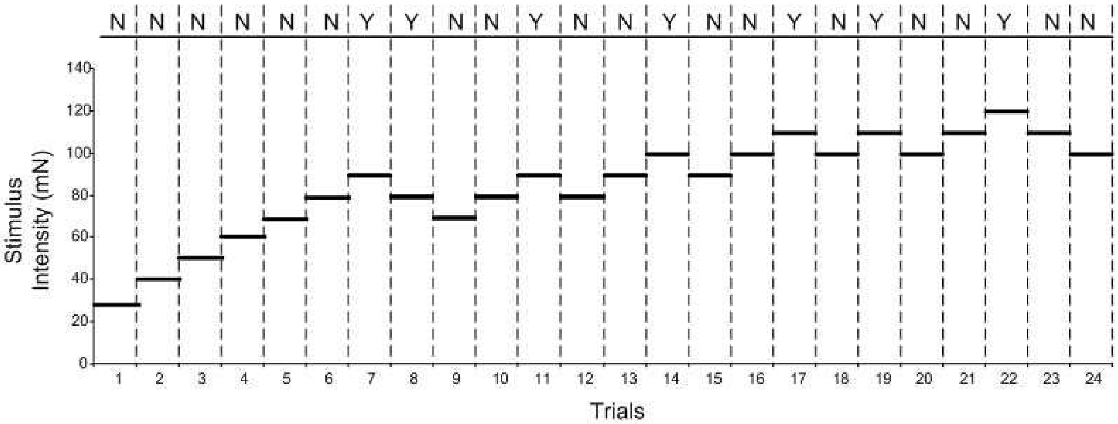


Figure 3.6: The staircases of the applied forces for participant OO. (*no*: N; *yes*: Y)

This procedure is repeated in three sessions for the three velocity ranges, low, medium, and high. Figure 3.6 shows the staircases of the force JND for one of the subjects in an experiment. Each subject is given training. The first session includes a familiarity phase and then the experiment is conducted for one of the velocity levels. In the second session, the subject does the same task with another velocity level. In the last session, the same task is done with the last velocity level.

The zero velocity is detected in the application of forces. The issue is encountered when the direction of motion frequently changes during a trial. For example, if the subject moves from left to right, the end-effector's velocity is positive. When the subject stops at the target and moves from right to left, the velocity's sign changes to negative, leading to a zero velocity at the targets. As a result, several sudden changes occur in the applied force, causing the device to switch discontinuously and jittering movement.

To overcome this problem, a model is developed using a narrow dead-zone as shown in Figure 3.7. In this model, if the velocity is within the velocity interval (dV), the applied force is set to zero by the dead-zone (dV). For these experiments, the |dV| of 0.001 m/s is found to be sufficient to solve the problem. Our model is

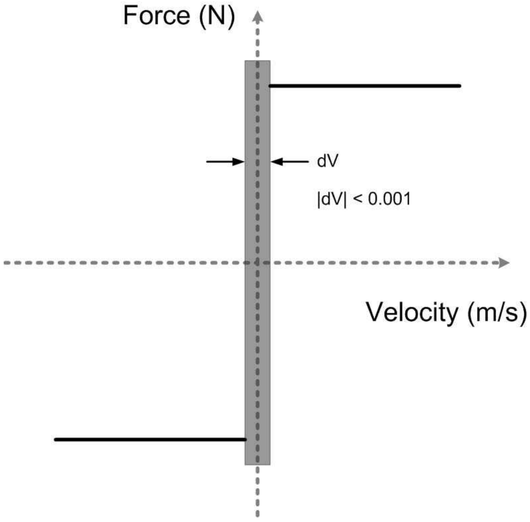


Figure 3.7: The zero velocity detection model: no forces are applied on the subjects' hands when the velocity is within the interval dV.

similar to the Karnopp [76] model, which represents friction force at zero velocity.

3.4 Results

The measured force JNDs are presented in Table A.1 in Appendix A for each subject. The average force JNDs across all subjects and for all levels of the velocity and force increment/decrement are shown in Table 3.1 and Figure 3.8. For example, the upper and lower limens of force JNDs are 18.91% (0.051 N) and 18.36% (0.049 N) when the subjects' hands are in the low velocity motion.

As shown in Figure 3.8, the average force JND values are in a range between 18.91% to 36.19% for force increment and 18.36% to 32.95% for force decrement, indicating that the force JNDs increase when the subject's hand velocity increases.

For the low velocity, the upper and lower limens are almost equal. However, the difference between the upper and lower limens slightly increases by increasing the

Rang of velocity (m/s)	Force Increment	Force Decrement	Average
Low (0.03-0.05)	18.91 ± 1.43	18.36 ± 0.9	18.63 ± 0.79
Medium (0.12-0.15)	27.08 ± 2.93	26.23 ± 2.85	26.66 ± 1.90
High (0.22-0.28)	36.19 ± 4.3	32.95 ± 3.00	34.57 ± 2.51
Average	27.39 ± 2.68	25.85 ± 2.21	

Table 3.1: The average force JNDs (%) of base friction force (0.27 N) and standard errors for all levels of the velocity and force increment/decrement across all subjects. The average JND of four subjects are included in each cell.

velocity. The upper limen is 4% higher than the lower limen for high velocity.

To study the effect of the velocity and force increment/decrement, a two-way analysis of variance (ANOVA) was conducted. Statistical analysis was performed using a mixed (within and between-subject) analysis of variance (ANOVA) with $p<0.05$ as the rejection level. SAS software was used for the analysis [77].

The average of force JNDs are calculated for the three ranges of velocity across the two levels of force increment/decrement and shown in Figure 3.9. This figure also shows that the velocity of the subject's hand has a significant effect on the force perception of the subject. For example, the force JND for high velocity is almost twice as large as the low velocity force JND with very small standard errors. The results of ANOVA in Table B.1 significantly supports the trend of increasing the force JND when the velocity increases in Figures 3.8 and 3.9, $F(2, 12) = 56.75$ and $p < 0.0001$.

The average of force JND were also calculated for the two levels of force increment and decrement across the three ranges of velocity and shown in Figure 3.10.

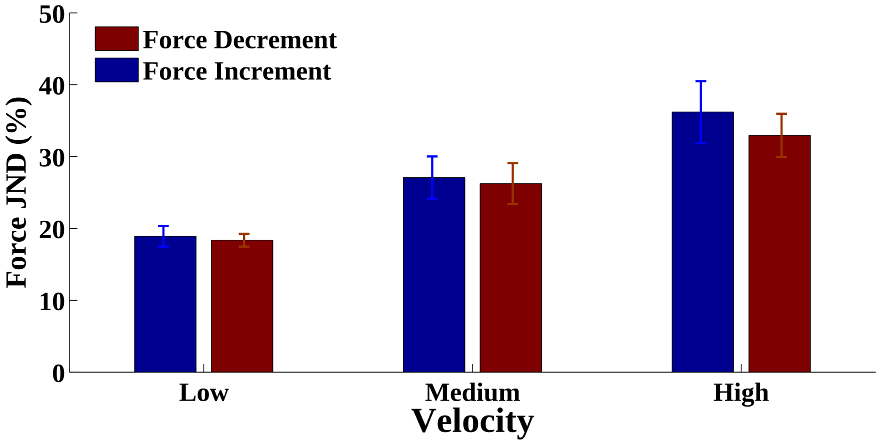


Figure 3.8: The average of force JND across all subjects and standard errors for the three levels of velocities and the two levels of force increment/decrement. The results of ANOVA significantly supports the trend of increasing the force JND when the velocity increases, $p < 0.0001$.

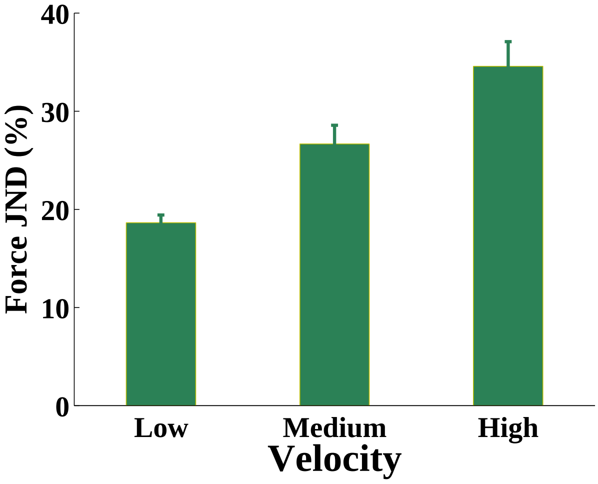


Figure 3.9: The mean values and standard errors of force JND for the three ranges of velocity across the force increment and decrement.

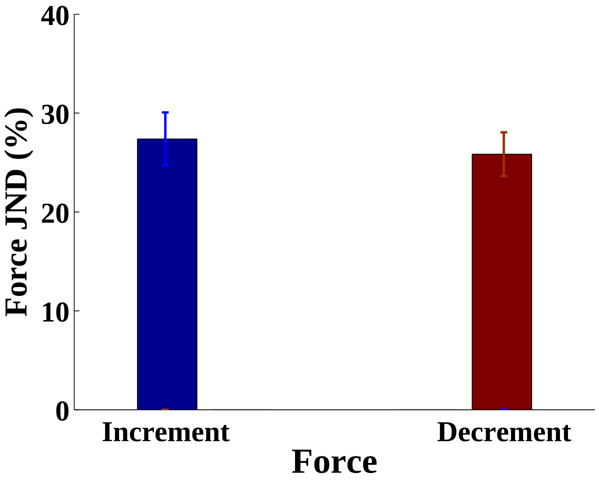


Figure 3.10: The mean values and standard errors of force JND values across all ranges of velocity. The results of ANOVA also show no statistically significant difference between the force increment and decrement, p = 0.6804.

As shown in the figure, the force increment and decrement are almost equal for all velocities, indicating that the upper and lower limens of force JNDs are somewhat symmetric. The results of ANOVA in Table B.1, F(1, 6) = 0.19 and p = 0.6804, also show no statistically significant difference between the force increment and decrement.

3.5 Discussion and Conclusions

In this chapter, an HEVE is constructed to study the effect of a user's hand velocity on force perception. An approach is presented to incorporate the velocity in the process of measuring the force perception threshold. The force JNDs are measured for three ranges of velocity. The trend of data, which is significantly supported by the results of an ANOVA, confirmed the hypothesis H_1, indicating that the force JND increases as the velocity of the user's hand increases in an HEVE.

The results also indicate that the upper and lower limens of force JND are almost equal for low and medium velocities, and the upper limen is slightly larger than the lower limen for high velocity motion. The results of an ANOVA also do not show any significant difference between the limens. In the next chapter, the difference between limens will be investigated for smaller and larger base forces.

The results show that the force JNDs measured in this chapter are larger than the JNDs measured by Jones and Pang [49, 50], who determined the force JND in a range of 7%–10% for different muscle groups in hand and arm under various conditions. For example, Pang et al. [50] found a JND that lies between 5% and 10% for pinching motions with a constant resisting force over base forces between 2.5 and 10 N.

Similarly, the force JNDs are higher than the JND measured in a VE by Allin et al. [48], who found a 10% force JND on the index finger with a constant base force at 2.25 N. On the other hand, the low velocity JNDs are compareable to the JNDs obtained in a VE by Brewer et al. [47] who found a 19.7% force JND for a 1.5 N base force. They also reported that their JND is larger than the JND in the literature, discussing several reasons such as the difference in the environment and tested joint, less subjects' training, and unfixed background dimensions.

In my study, the small base force (0.27 N) can be the main reason that the JNDs are larger than the JNDs measured by [50, 49, 48]. The base force is much smaller than their base forces (1.5–10 N), and according to Weber's law, the JNDs for low base stimuli are larger than ones for high base stimuli. In the next chapter, this difference will be investigated with different base forces to find if the higher JND in this study is due to a small base force.

An adaptation to applied forces was also observed among six out of the eight subjects. For instance, as shown in Figure 3.6, subject OO was adapted to applied forces. He could notice 0.08 N force on his hand on trial 8; however, he was not able to notice the same force on trials 10 and 12. Eventually, he could not notice 0.11 N force on trials 21 and 23. It appears that he would gradually lose his sensitivity to force if the experiment continued. In the next chapter, the adaptation will be investigated by a variation of staircase method, interweaving staircase method, to ensure that the adaptation has not been caused by the staircase method.

Chapter 4

Factors Affecting User Performance and Force Perception in HEVEs

4.1 Introduction

In this chapter, the force JNDs of the human haptic system are quantified and the following topics are studied.

1) The effects of the base force intensity and the force increment/decrement on the force JND of the human haptic system.

2) The effects of applied forces on the subject performance in an HEVE.

3) The adaptation of the subject's kinesthetic sense to forces in an HEVE.

An experiment is conducted for three levels of base force intensity. The Interweaving Staircase (IS) [68] method is employed to measure the force JNDs. For the first level, 0.15 N force is applied in the same direction as the hand motion to partially cancel the backdrive friction of the haptic device (0.27 N). Therefore, the resulting resistive force on the subject's hand is 0.12 N, which is the first level of base force. This level is called the *low* base force.

For the second level, 0.15 N is applied in opposition to the direction of the hand motion. This force adds to the friction force, resulting in a 0.42 N resistive force on the subject's hand. This force is called the *medium* base force.

For the third level, 0.5 N is applied in opposition to the direction of subject's hand motion, resulting in 0.77 N force on the user's hand. This is called the *high* base force. Thus, the three resultant base forces are 0.12 N (low), 0.42 N (medium), and 0.77 N (high); two greater than the friction and one smaller.

The hypotheses are presented in the next section, and the experiment is described in detail in Section 4.3. The results are presented and discussed for the force JND in Section 4.4.1, for the subject's performance in Section 4.4.2, and for adaptation in Section 4.4.3. Conclusions are presented in Section 4.5.

4.2 Hypotheses

In the previous chapter, H_1, which is that the force JND increases when the velocity of user's hand increases, was tested. In this chapter, the following hypotheses are proposed and tested. These hypotheses are based on the results in Chapter 3. H_2 is examined to investigate why the measured force JNDs in the previous chapter were larger than the JNDs in the literature. H_3 is tested to find any significant difference between the upper and lower limens of force JND for a relatively high velocity motion and different base forces. The adaptation effect observed in the previous chapter is also examined by H_5 using another psychophysics method. In addition, the effects of sub-threshold force are investigated by testing H_4.

H_2**:** Weber's law holds for force perception in an HEVE even when the user's hand is in motion. The force JND is larger for very small base force intensities and decreases as the base force intensity increases.

H_3**:** The upper and lower limens of force JND are not symmetric for all base forces when a subject's hand is in motion.

H_4**:** The accuracy of subject's movement is affected by increasing or decreasing the sub-threshold forces on the subject's hand in an HEVE.

H_5**:** Subjects lose sensitivity to changes in force as they carry out a motion task for an extended period of time in an HEVE.

4.3 Methods

This section describes the experimental setup and procedure of the experiment. The intensity of the base force is the only difference between the three levels of the experiment.

4.3.1 Participants

There were 16 participants (eight females and eight males) between the ages of 22 and 33. All were regular computer users and students at the University of Waterloo. They were right-handed, and had no more than trivial previous exposure to haptic interfaces. The participants did not have any neurological illness or physical injury that would impair hand function or force control ability. The participants were recruited by word of mouth and received $40 for their participation in the experiment. The experiment is conducted in accordance with the University of Waterloo ethical guidelines. Consent letters were obtained from all participants. The University of Waterloo office of research approved the experiment as Research Involving Human Participants (ORE #: 12738).

4.3.2 Apparatus

In this experiment, the same haptic device and monitor are used as in the previous chapter. A 2D VE is created using V-Realm Builder [71] and graphically rendered to users using MATLAB Virtual Reality Toolbox Viewer [72] through the 17" LCD monitor. The VE is haptically rendered to subjects using the proSENSE toolbox [70] via the haptic device. As shown in Figure 4.1, the VE contains a 2D red ball and two green rectangles (targets). The center-to-center distance between the targets is 10.2 cm, and the width of the target is 1.3 cm in display coordinates and in the haptic device space. The ball represents the position of the end effector (grasped by the subject's hand). When the subject moves the end-effector, the ball moves on a horizontal line.

4.3.3 Design

A Repeated Measures (within subject) design [78] is employed in this experiment. Therefore, each subject is required to participate in all levels of the experiment plus a one-hour training session. The order of levels are randomly assigned to the subjects.

The base force intensity and the force increment/decrement are the independent variables. The base force intensity have three levels; low, medium, and high. The force increment/decrement factor have two levels based on the relative changes from the base force. At the half of trials in each base force level, the force increases

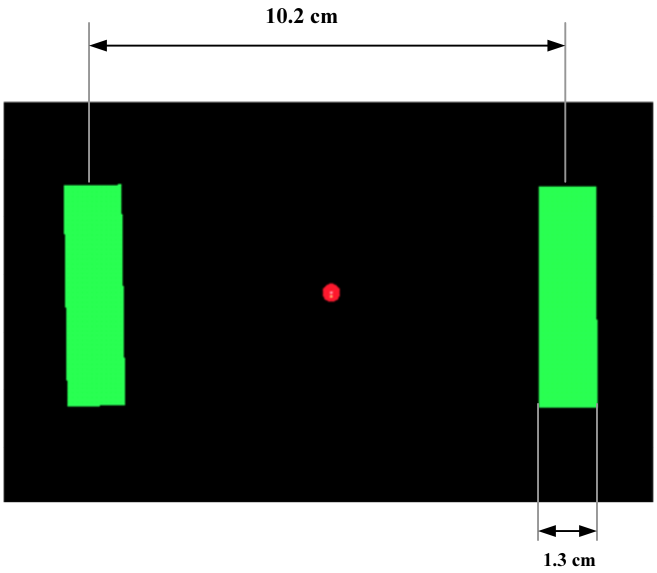


Figure 4.1: The 2D virtual environment that contains a red 2D ball and two green rectangles.

from the base force, and at the other half, force decreases. The two levels of force increment/decrement are called increment and decrement.

4.3.4 Procedure

Similar to the experiments in Chapter 3, the subject is seated on a chair facing the monitor and asked to place their right elbow on a side support. The wrist of the right hand is restrained with a wrist guard as shown in Figure 4.2, so that wrist movements are locked (to ensure that the subject just rotates his/her hand about his/her elbow). The subject grasps the device end-effector. Once the subject is seated comfortably, his/her right arm and fingers are shielded from his/her own view with an opaque barrier. Attention is directed to the monitor, which is placed approximately 70 cm from the subject.

As shown in Figure 4.3, each trial begins and ends with verbal commands (start

Figure 4.2: The subject grasps the device end-effector while he places his right elbow on a side support.

and stop). Subjects start a Fitts' type task when they hear start from the experimenter. The task is explained later in *Fitts' Type Task* subsection. Subjects stop and let go of the end-effector when they hear stop, and wait for 5-15 seconds before starting the next trial. During that time, no force is applied on the subject's hand, and the subject's hand is not in motion. Each trial has two intervals, and each interval lasts 15 seconds.

Figure 4.4 shows all trials of a level of the experiment. Figure 4.3 shows the first three trials in Figure 4.4. In trial 1, the first force (F) is continuously applied on the subject's hand from the beginning of the trial until the end of the first interval. This force is 0.15 N in the same direction as the hand motion for low base level. The force vector is shown in Figure 4.5 as the aid force. The force is a 0.15 N for medium and a 0.5 N for high base levels. These forces are in opposition to the direction of the hand motion, and shown in Figure 4.5 as the opposed force. The relative direction of applied force to the hand motion does not change during an experiment.

At the beginning of the second interval, the second force is applied to the subject's hand. This force is either an increment or decrement from the first force. The trials with a force increment and decrement called *force increment* and *force decrement* trials, respectively. Each base force level of the experiment consists of 48 trials: 24 increment and 24 decrement trials. The order of trials was randomly chosen by the experimenter before starting the experiment. As shown in Figure 4.4, the trial numbers are presented on the top and bottom of the stairs. For example, trials 1 and 2 are among the force decrement trials, and trials 3 and 8 are among the force increment trials.

The subjects are asked to detect changes in force value at the end of each trial. They respond with *yes* if they sense a force increment or a force decrement. They respond with *no* if they do not notice any changes. The subject's responses are

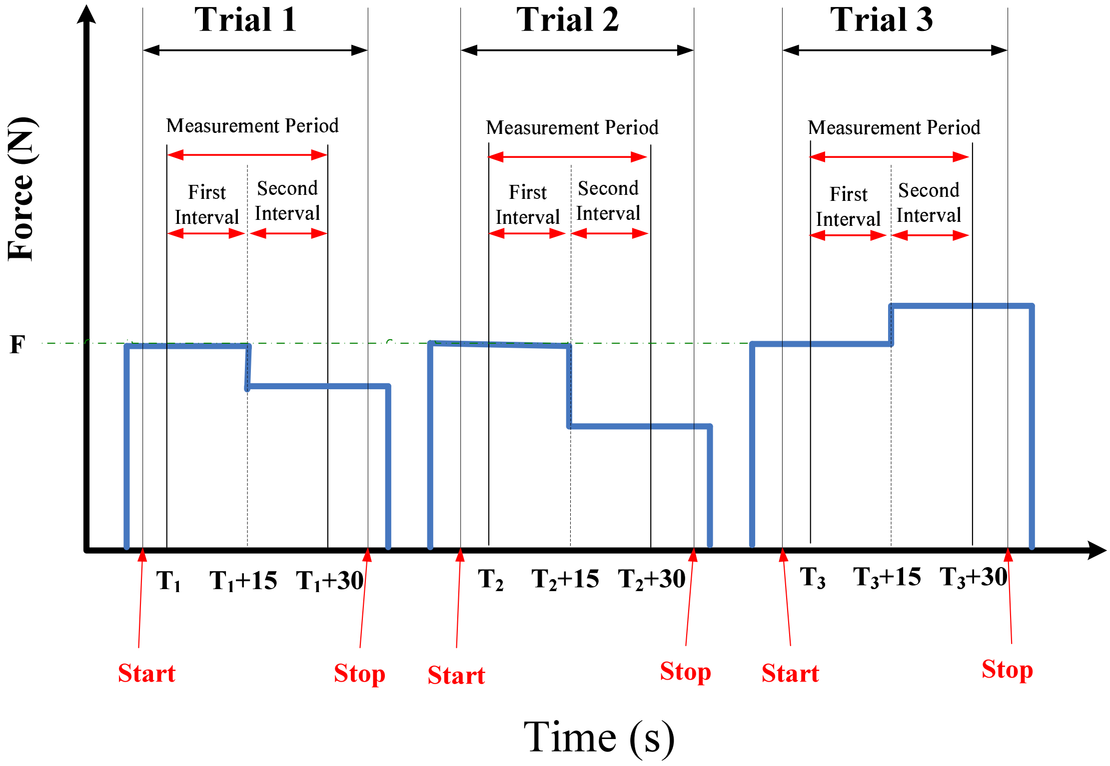


Figure 4.3: The first three trials of the experiment in Figure 4.4 (Times indicated are in seconds.)

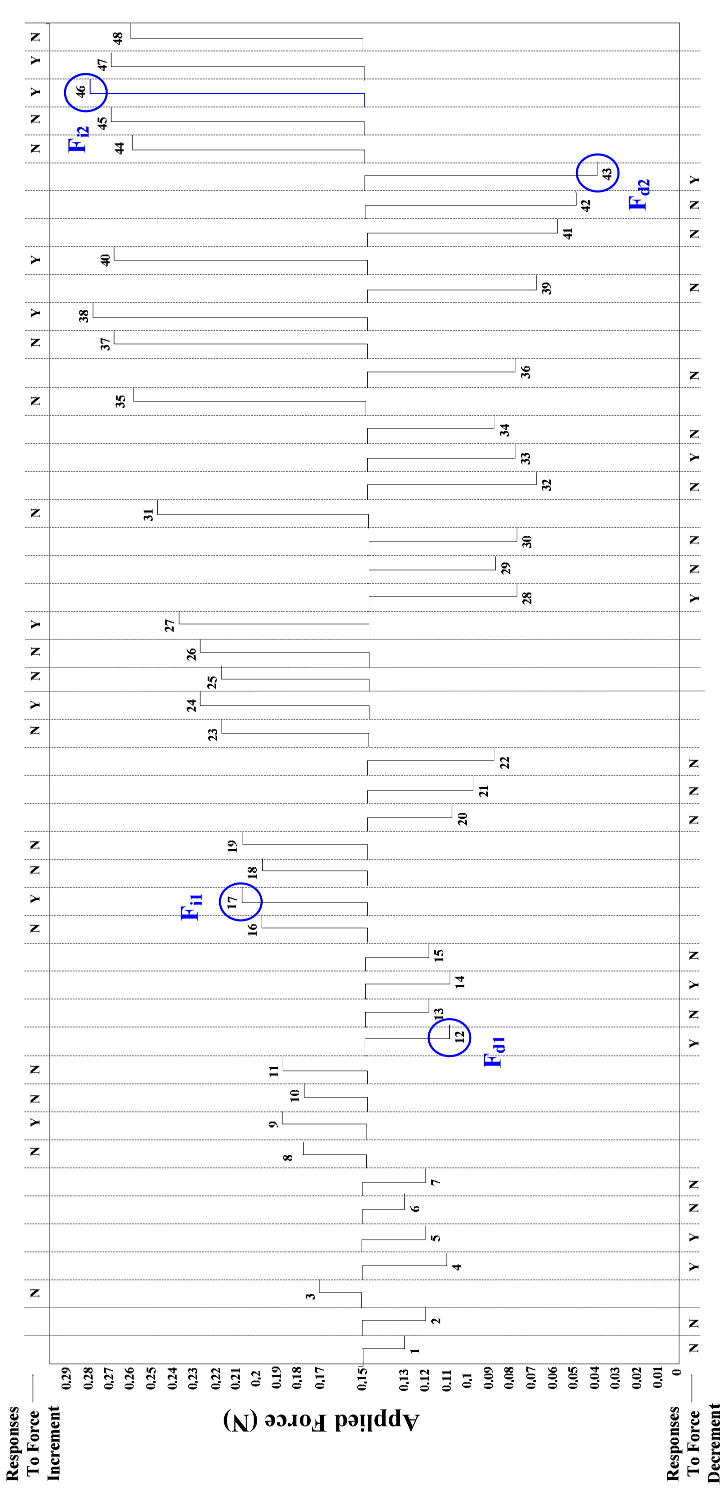


Figure 4.4: The interweaving staircase of forces for one subject. (N = *no*, Y = *yes*.)

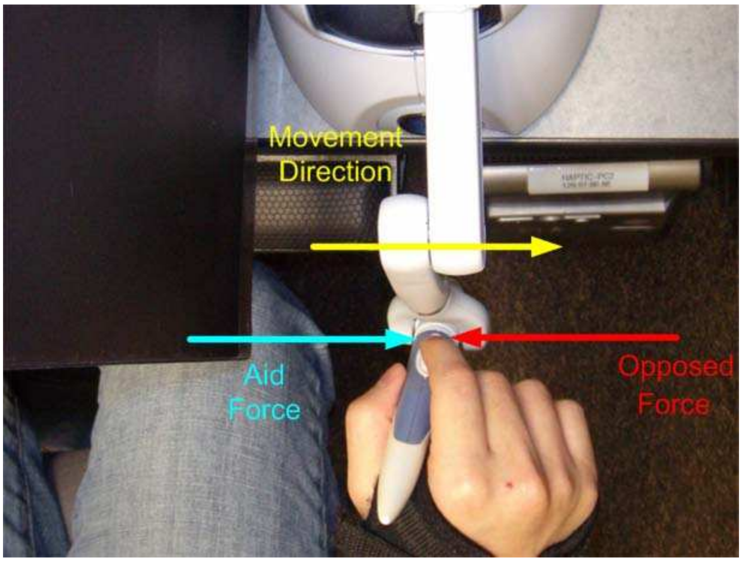


Figure 4.5: The opposed and aid force vectors.

shown on the top and bottom of Figure 4.4 for force increment and decrement trials (N = *no*, Y = *yes*.) The trials with *no* and *yes* responses are called *unnoticed* and *noticed* trials, respectively. For instance, trial 1 is an unnoticed trial because the subject's response is No.

The force is increased/decreased by 0.02 N in the first trial of both force increment and decrement trials, trials 3 and 1 in Figure 4.4. The values of the force increment/decrement in next trials are determined based on the response of the subject in the current trial. Two variables are initialized by 0.02 N. One variable, which is called ΔF_{Inc}, saves the increment value for the next force increment trial, and the other one, ΔF_{Dec}, saves the force decrement value for the next force decrement trial. These variables would increase by 0.01 N if the response was No, and would decrease by 0.01 N if the response was *yes*. For example, ΔF_{Dec} value for trial 2 is 0.03 N (0.02 + 0.01) because the response is *no* in trial 1. Therefore, 0.15 N decreases by 0.03 N, and 0.12 N is applied at the second interval of trial 2. ΔF_{Dec} value would decrease by 0.01 if the response was *yes*.

The points at which the subject's response changes from *yes* to *no* or vice versa are called transition points. The direction of the force increasing/decreasing is reversed from increasing to decreasing, or vice versa at these points. For example, trial 9 is a transition point because the response in trial 8 was *no* and at trial 9 is *yes*. Therefore, for trial 10, ΔF_{Inc} is decreased by 0.01 N.

At the beginning of the experiment, the subject's responses might not be valid due to unfamiliarity with the type of force sensation. Thus, the first two transition points are neglected [79]. The force JND is the average values of the third transition point to the last one. Hence, in Figure 4.4, the upper limen of force JND (force increment) is 0.925 N. This is the average of force values at the transition points (trials 17, 18, 24, 25, 38, 44, 46 and 48). To find the JND in %, this force value should be divided by the base force.

Fitts' Type Task

In each trial, the subject engages in a task similar to the Fitts' task, which is described in detail in Section 2.1.1. Since the effects of applied forces on accuracy are investigated, a fixed index of difficulty (ID), 4, is chosen for all experiments. In other words, if there is a change in accuracy, it would be due to the changes of applied forces on the subject's hand.

During the trial, subjects are asked to tap the two targets (green rectangles) by moving their hand to left and right. Each time the ball is within one of the targets, a hit is scored by subjects. An overshoot error occurs if they pass the target. An undershoot error happens if they did not reach the target. Subjects are asked to score as many hits as they can and carry out the task as rapidly as possible and as accurately as possible for a predetermined duration.

Unlike the Fitts' task, subjects are required to maintain their hand velocity within a specified range because the goal is to investigate the effect of forces, not the subject's hand velocity, on subject performance. The reference velocity range is set by the experimenter to 0.16-0.20 m/s based on the ability of a subject to carry out the task with an acceptable range of missing error (less than 15%). The missing error equals the sum of overshoots and undershoots divided by the total hits, overshoots, and undershoots. A training session is delivered to help subjects to get familiar with the task. It is required for subjects that carry out the task with less than 15% missing error at the end of training session and prior to the beginning of the experiment.

In this setup, similar to the previous chapter, the colour of the ball is also determined based on the hand's velocity and the reference velocity to help a subject to keep the hand's velocity within the range. If the subject's velocity is within the range, the ball's colour is red; otherwise its colour is yellow. The mean velocity value is monitored as it does not rapidly change when the subject stops at the target.

As shown in Figure 4.3, each trial has a measurement period, including two 15-second intervals (before and after force increment/decrement). The first interval is started when the experimenter ensures that the hand's velocity is within the reference range. The number of hits, overshoots, and undershoots are separately measured during each interval.

4.4 Results and Discussion

The results of the experiment are presented and discussed in the three following subsections. The measured force thresholds and factors affecting on the force thresholds are presented in section 4.4.1. Then, the results of the subject's performance and accuracy are shown and discussed in Section 4.4.2. Finally, in Section 4.4.3, the effect of adaptation is discussed based on the analysis of applied forces.

Base force Intensity	Force Inc./Dec.	Mean JND (%)	Standard Deviation	Standard Error
Low	Increment	64	22.36	5.59
Low	Decrement	43	17.47	4.37
Medium	Increment	15	6.93	1.73
Medium	Decrement	12	3.79	0.95
High	Increment	10	3.72	0.93
High	Decrement	11	3.76	0.94

Table 4.1: The average force thresholds (%), standard deviations, and standard errors for all levels of the base force and force increment/decrement.

4.4.1 Force Thresholds

The measured force JNDs are presented in Table A.2 for each subject. The average of JND values for all levels of the two factors are shown in Table 4.1 and Figure 4.6.

The result is analyzed using the repeated-measures (within subject) Analysis of Variance (ANOVA). The analysis is done at a significance level of 0.05. SAS software is used for the analysis [77].

As shown in Figure 4.6, there are several trends present in the data. One trend shows that the base force intensity has a major effect on the force JND. The force JND significantly decreases by increasing the base force intensity. The figure also shows a significant difference between the force increment and decrement of the low base force. The difference decreases for the medium and high base forces, indicating that there is an interaction between the base force intensity and force increment/decrement. The results of a two way ANOVA, $F(2, 30) = 12.28$ and $p < 0.0001$, also confirm the interaction between the base force intensity and force increment/decrement. The details of ANOVA results are presented in Table B.2.

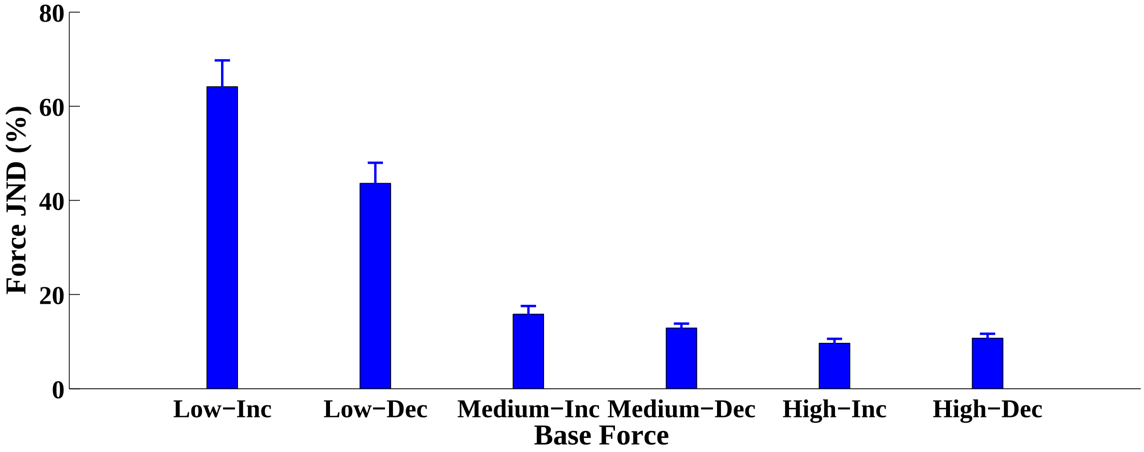


Figure 4.6: The average and standard errors of force JND values for all subjects. (Inc = Force Increment, Dec = Force Decrement)

The results of a post-hoc Tukey test also confirm the large difference between the force increment and decrement of the low base force ($p < 0.0001$). This difference shows that the subjects notice the decrements of the low base force, Low−Dec, more easily than the increments, Low−Inc. This might be due to the fact that force is applied in the same direction of hand motion and the total resistive force is decreased on the subject's hand. This result rejects the null hypothesis in favour of H_3 hypothesis. In other words, the upper and lower limens of low base force JND are not symmetric.

The results in Figure 4.6 show a Weber trend, which is explained in Section 2.2.1. The force JND is noticeably large for the low base forces and decreases for the medium and high base forces. The results of the post-hoc test show a significant difference between the JNDs of the low base inc/dec and the medium or high base inc/dec ($p < 0.0001$). These results support the significant effect of the base force intensity on the force JND, rejecting the null hypothesis in favour of H_2 hypothesis.

In the previous chapter, the force thresholds are determined with respect to a friction base force (0.27 N); however, that was for a different velocity range. To find the JNDs for the same velocity as the velocities implemented in this chapter,

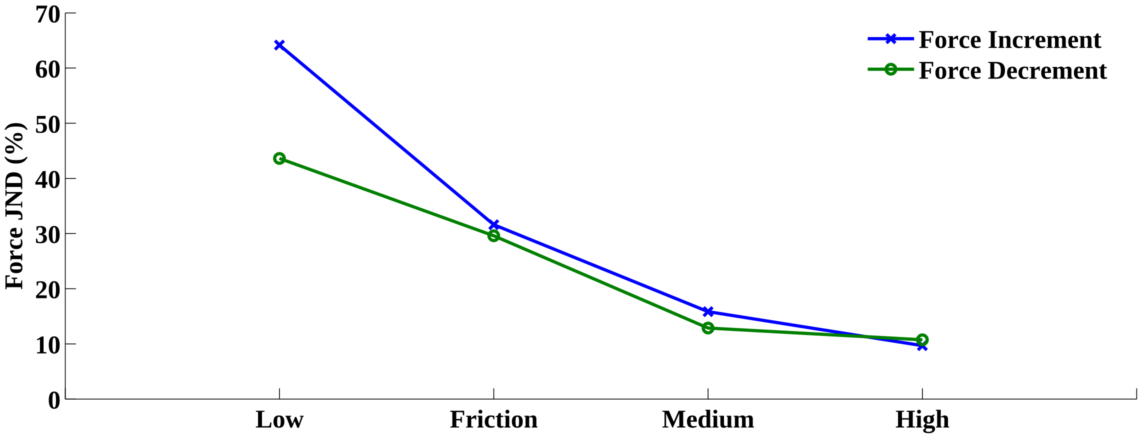


Figure 4.7: The Weber's fraction for four base force intensities.

the JNDs for the friction are estimated based on a linear interpolation of JNDs for two ranges of velocities (0.12-0.15 and 0.22-0.28 m/s). The resulting force JNDs are 31.6% and 29.6% for the upper and lower limens of the friction base force. Figure 4.7 shows a Weber trend for the JNDs measured in the current and previous chapters, confirming that the JNDs of small base forces are larger than high base forces' JNDs. The JNDs for friction base forces are smaller than the low base force JNDs and greater than the medium base force JNDs.

Figure 4.6 do not show any significant difference between the force increment and decrement of the medium and high base forces. In other words, the upper and lower limens of JND are somewhat symmetric for medium and high base force intensities. The results of the post-hoc test also show no significant difference (p = 0.9433 for medium and p = 0.9995 for high).

The results show that, for applications that require motion within a constant velocity range, the JNDs are in the extremely small base force region of the Weber's fraction, very close to the absolute threshold of the human haptic system. For example, the low base force JNDs (62% and 38%) are comparable with the JNDs measured by Raj et al. [51], who found that the human sensitivity is very low for small weights (20-60 g). Their results (JNDs ranging between 89% and 35%)

indicate that as the base weights increases, JND decreases and remains relatively constant at weights above 200 g.

The standard errors (or standard deviations) of the low base force JNDs are greater than the JNDs of the medium and high base force. This indicates that the subjects are more confident in their reports about the medium and high base force JNDs.

The medium and high base force JNDs (around 13%) are very similar to the JNDs measured by Raj et al. [51] who studied the ability of human subjects to discriminate between different magnitudes of weights. Their results show a JND of 12%-13% for relatively large base weights (80-200 g) lifted by the middle finger. The medium and high base force JNDs are also similar to the JNDs obtained by Jandura and Srinivasan [64], who found 12.7% torque JND when the reference torque was 0.06 Nm.

The high base force JNDs (around 10%) are very similar to the JNDs measured by other researchers [48, 49, 50]. They found JNDs in a range of 7%–10% for different muscle groups in hand and arm under various conditions. Jones [49], in a force matching experiment about the elbow, found a JND ranging between 5% and 9% over a range of different base forces. Pang et al. [50] found a 5% to 10% JND for pinching motions between the finger and thumb with a constant resisting force over base forces between 2.5 and 10 N. The high base force JNDs are almost the same as the JND measured in a VE by Allin et al. [48] using the PHANToM^{TM} Omni device. They found a 10% force JND on the index finger with a constant base force at 2.25 N.

Our medium and high base force JNDs are much smaller than the JNDs obtained in a VE by Brewer et al. [47] who found a 19.7% force JND (base force: 1.5 N) for the index finger of young subjects (ages 18-35) and a 31% force JND (base force: 2 N) for elderly subjects (ages 61-80). They confirmed that their JNDs are relatively high and discussed reasons why their JND is larger than the JND in the literature such as the difference in the environment and tested joint, less subjects' training, and unfixed background dimensions.

4.4.2 Subject's Performance

The average number of overshoots (OS), undershoots (US), and hits (Hit) in unnoticed and noticed trials are calculated and presented in Table A.3 and Table A.4 in Appendix A. The tables show the data for each subject and all levels of the base force intensity and force increment/decrement.

Performance before the force increment/decrement

Although the main goal of this study is to investigate the effects of sub-threshold force increment/decrement on subject performance, the effects of continuous forces are also investigated using the data collected in the first interval of measurement period (before the force increment/decrement). The average movement time (MT), missing error, and index performance (IP) of before force increment/decrement are calculated across all subjects and presented in Table 4.2.

There should not be a significant difference between the IP values for force increment and decrement trials because there was no force increment or decrement in the first measurement interval. As shown in Table 4.2, the results of MT and IP values do not show any significant differences between the force increment and decrement at each base force level, indicating that the random error is fairly small when there is no force increment or decrement. For example, the IPs are 7.87 bits/s and 7.86 bits/s for the low base force increment and decrement. The ANOVA results on the IP in Table B.3 also confirms the trend, F(1, 15) = 0.68 and p = 0.4226.

Base force Intensity	Type of Trials	Movement Time (s)	Missing Error (%)	Index Performance (bits/s)
Low	Increment	0.5068 ± 0.0034	5.91 ± 0.50	7.87 ± 0.09
Low	Decrement	0.5091 ± 0.0032	5.78 ± 0.46	7.86 ± 0.09
Medium	Increment	0.5037 ± 0.0038	5.54 ± 0.47	7.94 ± 0.10
Medium	Decrement	0.5034 ± 0.0034	5.60 ± 0.38	7.95 ± 0.09
High	Increment	0.5009 ± 0.0046	5.02 ± 0.54	7.98 ± 0.13
High	Decrement	0.5029 ± 0.0045	5.15 ± 0.48	7.95 ± 0.13

Table 4.2: The average movement time, missing error, IP (bits/s), and standard errors across all subjects for the before force increment/decrement data.

The IP values slightly increases when the base force increases, suggesting that the effect of base force is not significant in the first interval of measurement period. The ANOVA results on the IP in Table B.3 do not show a statistically significant effect of the base force on the subjects' IPs, F(2, 30) = 1.53 and p = 0.2330. In the original Fitts' study, there was also a very small increment when a one-pound-stylus was used instead of the one-ounce-stylus. The IP increased from 10.75 by 0.06 bits/s for ID = 4. Wall and Harwin [36] also reported a little difference in the IP values between the haptic and non-haptic conditions. Similarly, Lee and Hannaford [34] reported a 0.1 bits/s improvement in the IP at base force as low as 0.05 N.

Our IP values are different from the IPs in Fitts (around 10 bits/s) because the value of the IP is dependent on several factors such as the type of input device, visual display, and experimental procedure. A large variation in the range of IP were reported by researchers [36, 80, 81], who conducted the Fitts' task using different types of input devices, visual displays, and experimental procedures. For example, Card [80] found an IP similar to Fitts' original IP for a mouse and an IP of roughly half this value for a joystick. Wall and Harwin [36] reported an average IP of 2.86 bits/s for ID $>$ 3 for a PHANToM haptic device. A PHANToM device was used by Chun et al. [81], who obtained the average IP values from 2.05 to 3.00 bits/s for four VR visual displays such as stereo goggles, mirror-reflection shutter glasses, shutter glasses, and a Cyberscope.

In addition, the difference in the procedure is important. For instance, Wall and Harwin [36] started each trial from the time that subjects tapped their first target. In the Fitts' task, the measurement period was started when subjects started the task from the middle point between the targets, and the subject's hand was not in motion before starting the task. In our study, a specific range of velocity was required for the task. Thus, the measurement period was started when the subject's hand velocity was within the range.

Missing errors are calculated by summing overshoot and undershoot errors shown in Table 4.2. The missing error data indicate that the missing error slightly decreases when the base force increases. For instance, the missing error is 5.91 % for the low force increment and 5.02 % for high force increment. In addition, the ANOVA results in Table B.4, F(2, 30) = 2.32 and p = 0.1153, do not show a statistically significant effect of the base force on the missing error. Similarly, Fitts [24] also reported a decrease of 0.56 % in missing error for ID = 4 when a one-pound-stylus was used, but the trend was not consistent with other IDs. Wall and Harwin [36], who used a PHANToM device, did not report their missing errors.

Performance after the force increment/decrement

The effects of force increment/decrement on subject performance in unnoticed and noticed trials are now investigated.

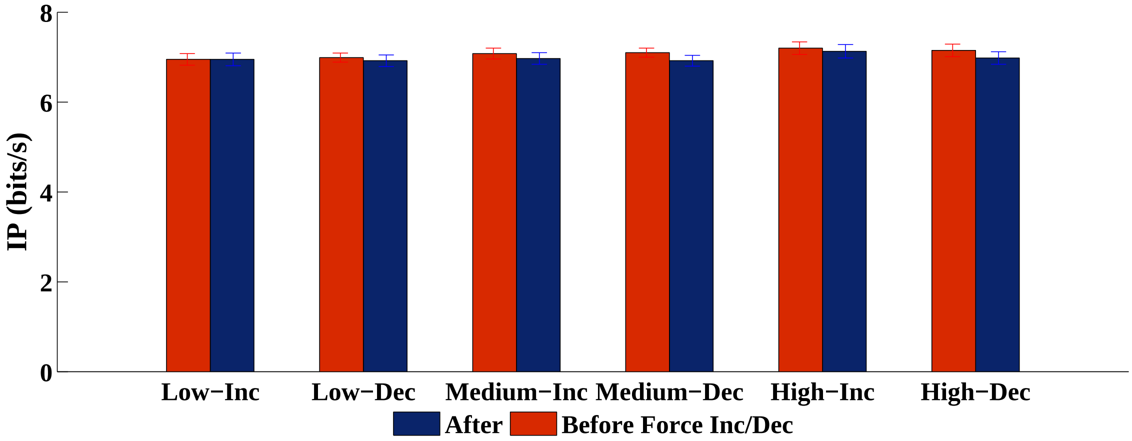


Figure 4.8: The average of IP and standard errors for the unnoticed data across all subjects (ID = 4.)

Effects of Unnoticed Forces

The average IP and missing error (ME) and standard errors for unnoticed data across all subjects is presented in Table A.5, Figure 4.8, and Figure 4.9.

As shown in Figure 4.8, the force increment/decrement does not have any significant effect on IP. The ANOVA results in Table B.5, F(1, 15) = 1.15 and p = 0.3010, also show no significant difference between the force increment and decrement, as well as no significant difference between the levels of base force, F(2, 30) = 1.2 and p = 0.3167.

In addition, the missing errors in Figure 4.9 do not generally show any significant effect of the force increment/decrement. It appears that there is only a difference between the missing errors of Medium-Dec, the medium base force decrement. However, the ANOVA results on the missing errors in Table B.6, F(1, 15) = 2.52 and 0.1331, do not indicate any significant difference between the levels of force increment and decrement, including Medium-Dec.

Although the results do not show any significant effect of force increment/decrement on IP and ME, relatively large variations in the overshoot and undershoot errors in-

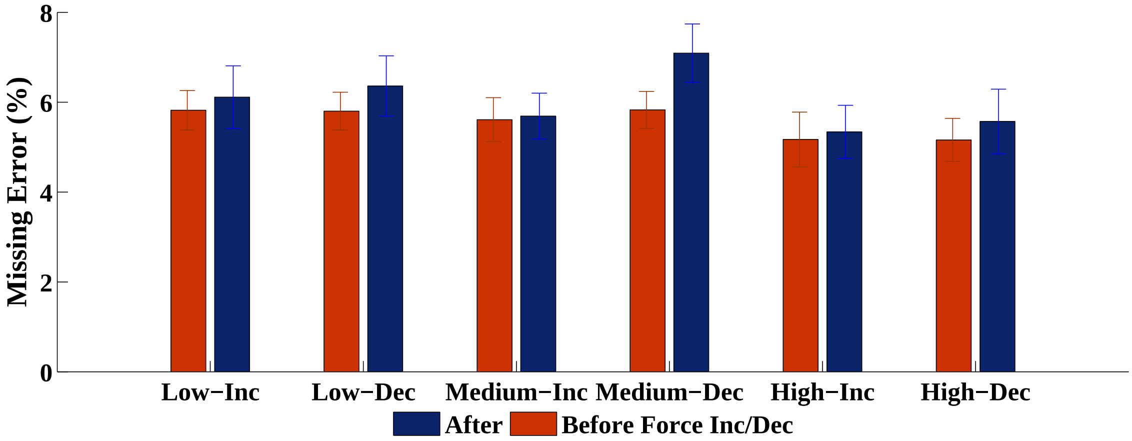


Figure 4.9: The average of missing error and standard errors for the unnoticed data across all subjects.

dicate that the force increment/decrement affect the accuracy of subjects. To study the variations in errors, the average values of overshoots, and undershoots across all subjects are calculated and normalized. The average percentage of overshoots (OS%) and undershoots (US%) for before and after force increment/decrement are presented in Table 4.3.

The effects of force increment/decrement are summarized in the *Sub-threshold Force Effects* column of Table 4.3, vertical arrows are used to show the changes in the errors. For example, overshoot error, OS%, decreases when the low base force increases. The trend of errors show that the overshoot errors decrease and increase by increasing and decreasing the unnoticed, sub-threshold, forces, respectively. In addition, the undershoot errors increase and decrease by increasing and decreasing the sub-threshold forces, respectively. These trends indicate that, when force is decreased, some of the hits turn to overshoots, and some of the undershoots turn to hits. On the other hand, when the force is increased, some of the overshoots turn to hits, and some of the hits turn to undershoots. Thus, the original Fitts' missing error, which is the sum of overshoots and undershoots, cannot show these effects of force increment and decrement on errors.

Base Force	Force Inc/Dec	Before Force Increment/Decrement			After Force Increment/Decrement			Sub-threshold Force Effects			Δ(OS-US)%
		OS%	US%	(OS-US)%	OS%	US%	(OS-US)%	OS%	US%	(OS-US)%	
Low	Inc.	3.99	1.83	2.16	2.78	3.36	-0.56	↓	↑	↓	-2.71
Low	Dec.	3.87	1.94	1.93	4.35	2.01	2.34	↑	↓	↑	0.41
Medium	Inc.	3.60	2.01	1.58	3.25	2.44	0.81	↓	↑	↓	-0.77
Medium	Dec.	3.51	2.32	1.18	4.49	2.60	1.89	↑	↑	↑	0.71
High	Inc.	3.40	1.77	1.62	3.06	2.27	0.79	↓	↑	↓	-0.83
High	Dec.	3.38	1.78	1.59	3.84	1.74	2.10	↑	↓	↑	0.51

Table 4.3: The average of overshoots (OS%), undershoots (US%), and their differences ((OS-US)%) in *unnoticed* trials across all subjects. Vertical arrows indicate the changes in the errors.

According to the trends of errors, it appears that the difference between overshoot and undershoot errors ((OS-US)%) can present the effect of force increment and decrement. Therefore, the differences between overshoot and undershoot errors ((OS-US)%) are calculated for each interval of the measurement period and presented in Table 4.3. For example, as shown in Figure 4.10, (OS-US)% is decreased from 2.16 to -0.56 after the increment of unnoticed force.

Δ(OS-US)%, which is the difference between the (OS-US)% of before and after force increment/decrement, is used as a performance index to study the effect of force increment/derement. Δ(OS-US)% values are presented in the last column of Table 4.3 and Figure 4.11. These results indicate that the accuracy is affected when the applied forces increase or decrease. For instance, the Δ(OS-US)% for medium force increment, -0.77%, is relatively smaller than the Δ(OS-US)% for medium force decrement, 0.71%.

The results of a two-way ANOVA on Δ(OS-US)%, which is presented in Table B.7, statistically support the significant difference between the force increment and decrement, $F(1, 15) = 27.49$ and $p < 0.0001$, rejecting the null hypothesis

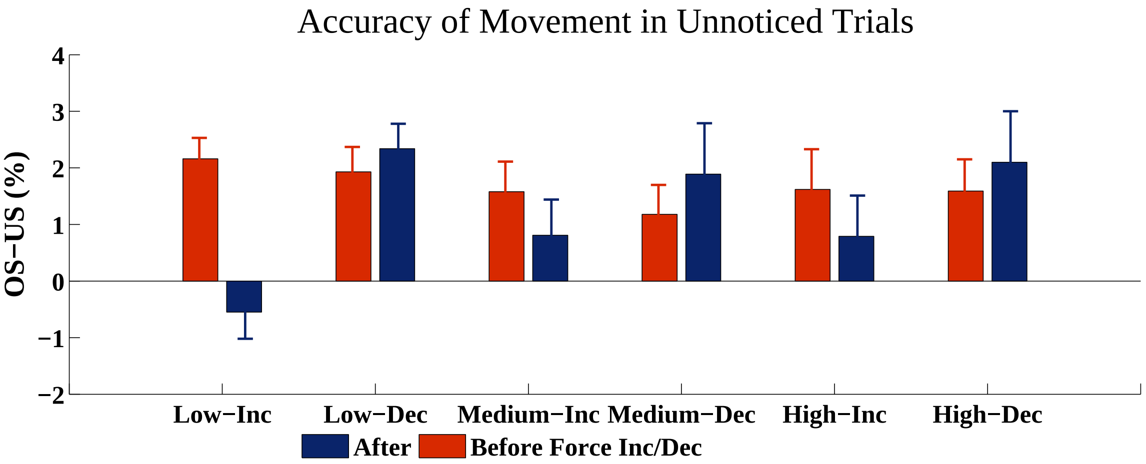


Figure 4.10: The average and standard errors of the difference between the numbers of overshoots and undershoots in unnoticed trials. (Inc = Force Increment, Dec = Force Decrement)

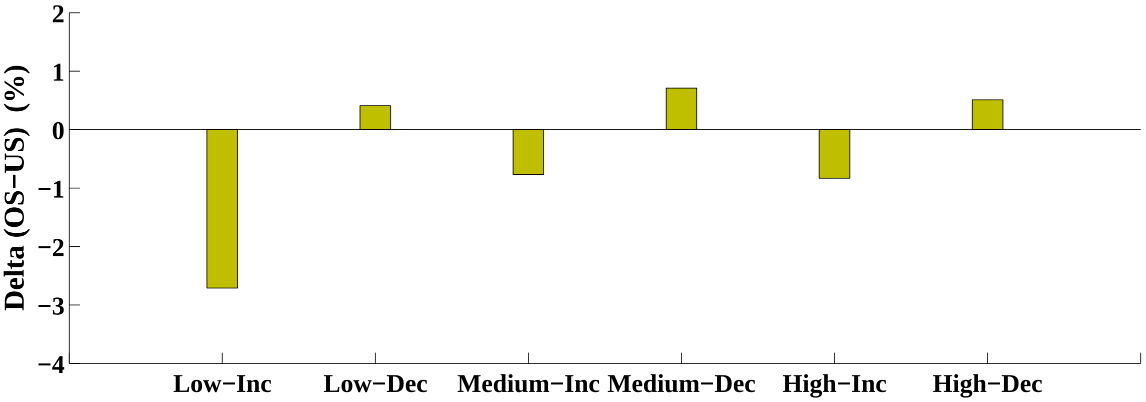


Figure 4.11: The average and standard errors of the Δ(OS-US)% in unnoticed trials. (Inc = Force Increment, Dec = Force Decrement)

in favour of H_4 hypothesis. As a result, the performance of users is affected by increasing and decreasing of the sub-threshold forces on their hands in an HEVE.

In addition, as shown in Figure 4.11, the base force intensity also affects the error rate. The Δ(OS-US)% of the low base force increment is much larger than other's. The ANOVA results in Table B.7 show a significant difference between the levels of base force, F(1, 15) = 4.19 and p = 0.0249, showing only that at least two of the base force levels are significantly different from one another. To find which base force is significantly different from another, a post hoc test is conducted. The results of the test show that the significant difference is between the low and medium or high base forces. Post hoc tests carry out a pair wise comparison test between the levels of a factor to determine which level is significantly different from another [78]. The results of post hoc test is presented in Table B.8.

The significant difference between low base and other base forces is due to the application of relatively large forces in the low force increment. As shown in Figure 4.7, the insensitivity of subject force perception for low base let the experimenter apply larger forces. These forces caused a relatively large error, increasing the errors for a low base force larger than the others.

Effects of Noticed Forces

The average percentage of overshoots (OS%), undershoots (US%), and their difference ((OS-US)%) in the first interval (before force increment/decrement) and the second interval (after force increment/decrement) for noticed trials are presented in Table 4.4 and Figure 4.12. Here, the same trend as in unnoticed trials are observed for noticed trials. Δ(OS-US)% is increased when the force is decreased, indicating that the subjects have less overshoots and more undershoots when the force increase compared to the time with the force decrease. However, as shown in Figure 4.13, there are differences between the magnitudes of Δ(OS-US)% for the

Base Force	Force Inc/Dec	Before Force Increment/Decrement			After Force Increment/Decrement			Noticed Force Effects			Δ(OS-US)%
		OS%	US%	(OS-US)%	OS%	US%	(OS-US)%	OS%	US%	(OS-US)%	
Low	Inc.	3.92	2.08	1.84	2.41	3.32	-0.91	↓	↑	↓	-2.75
Low	Dec.	3.68	2.07	1.61	4.82	1.50	3.32	↑	↓	↑	1.71
Medium	Inc.	3.50	1.97	1.54	3.65	2.54	1.11	↑	↑	↓	-0.43
Medium	Dec.	3.31	2.06	1.25	4.17	2.08	2.08	↑	↑	↑	0.84
High	Inc.	3.26	1.62	1.64	2.88	2.28	0.60	↓	↑	↓	-1.04
High	Dec.	3.44	1.69	1.73	4.09	2.37	1.74	↑	↑	↑	0.01

Table 4.4: The average of overshoots (OS%), undershoots (US%), and their differences ((OS-US)%) in *noticed* trials across all subjects.

noticed and unnoticed data. For example, Δ(OS-US)% of noticed data is almost zero for High-Dec and almost 3 times of the unnoticed Δ(OS-US)% for Low-Dec.

The results of a two-way ANOVA followed by a Tukey post-hoc test only support the significant difference between the low base force increment and decrement, $p <= 0.0001$. The analysis does not support the trend for other base forces because the number of noticed trials is much smaller than the unnoticed trials, reducing the power of experiments for noticed trials. For example, as shown in Figure 4.4, the number of noticed trials is 7, and the rest, 17 trials, are unnoticed trials for force increment. The results of the two-way ANOVA are presented in Table B.9, which shows an interaction between the base force and force increment/decrement.

4.4.3 Adaptation

An adaptation to applied forces is observed in the results. For instance, as shown in Figure 4.4, the subject adapts to applied forces. She noticed 0.21 N on her hand on trial 17; however, she could not sense 0.27 N on trials 37 and 45. She would lose gradually her sensitivity to force if the experiment continued. This adaptation is

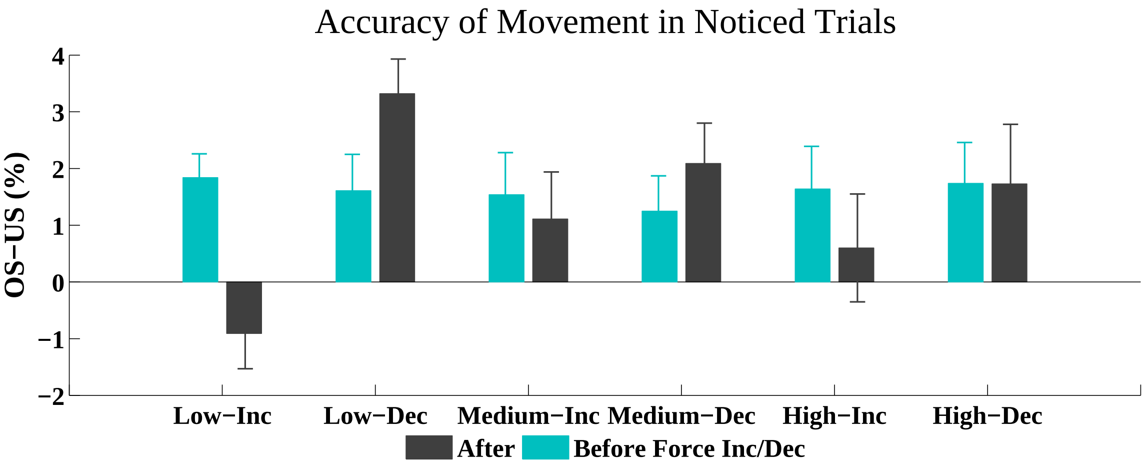


Figure 4.12: The average and standard errors of the difference between the number of overshoots and undershoots in noticed trials. (Inc = Force Increment, Dec = Force Decrement)

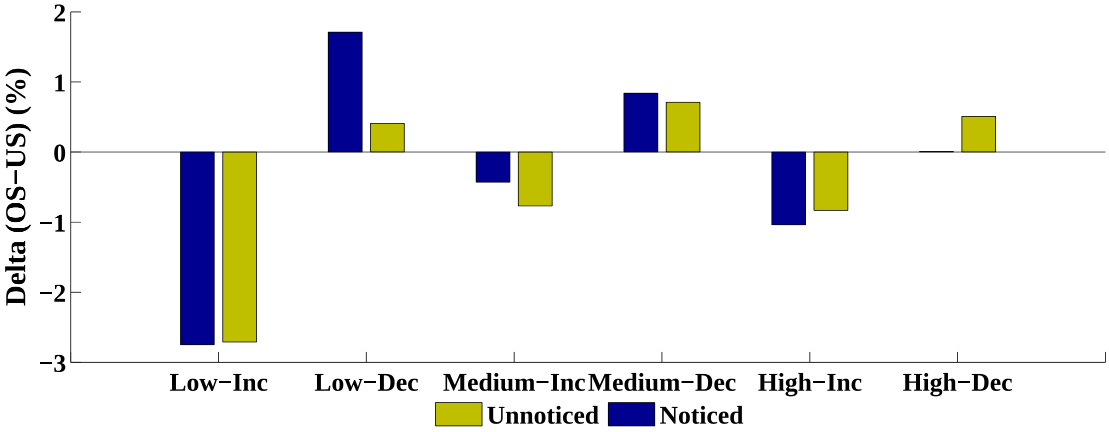


Figure 4.13: Noticed vs. unnoticed data for the difference between before and after force increment/decrement.

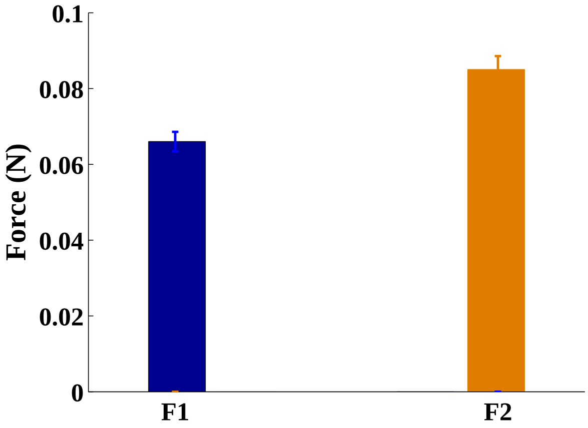


Figure 4.14: The averages and standard errors of applied forces across all levels of the base force and force increment/decrement.

investigated by selecting two forces from each subject's data in each experiment.

As shown in Figure 4.4 in Section 4.3.4, two forces are selected from force increment or decrement trials to investigate the adaptation effects. The first force (F1) is the force that is presented in the second sequence of the *yes* trials. It occurs early in the trial at approximately trial 14. The second force is taken later in the series at approximately trial 45. The second force (F2) is presented in the last trial of the *yes* trials. Both trials are after a *no* trial. In Figure 4.4, for example, F1 is the force applied at trial 17 and F2 is the force applied at trial 46 in the force increment trials.

The average of both forces and standard errors across all subjects and experiments are shown in Figure 4.14. As shown in the figure, the trend is that the F2 is higher than F1 when averaged across all conditions. This indicates that subjects lose sensitivity to changes in force as they carry out a simple motion task for an extended period of time. A one-way ANOVA on the force showed that this trend was significant, $F(1, 15) = 19.95$; $p < 0.0005$, rejecting the null hypothesis in favour of H_5 hypothesis. The details of ANOVA results are presented in Table B.10.

Figure 4.15 shows the average of both forces and standard errors for the levels

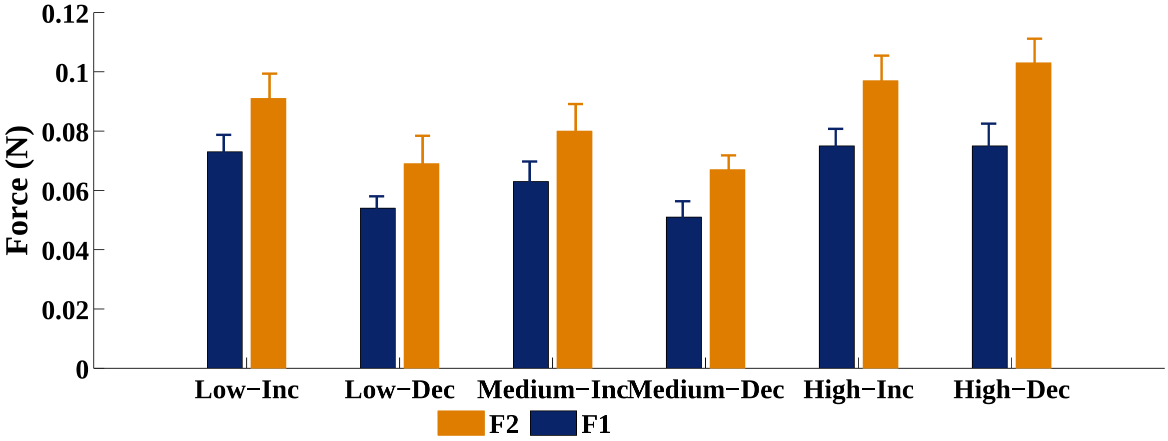


Figure 4.15: The averages and standard errors of applied forces as a function of the base force and force increment/decrement.

of the two factors. As shown in Figure 4.15, there are several trends present in the data. The first is that F1 and F2 for the low and medium base force decrement are smaller than the force increment; however, F1 and F2 for high base force decrement is slightly larger than the force increment's. This interaction between the base force and force increment/decrement is independent of F1 and F2. In other words, this interaction is similar for both of F1 and F2. The second trend, similar to the trend in Figure 4.14, shows that F2 is higher than F1 for each level of the base force and force increment/decrement. The third one indicates that the difference between F1 and F2 for a high base force is larger than the difference for other base forces.

A two-way ANOVA is conducted on the difference of forces (F2-F1) for the base force and force increment/decrement. The results, F(1,15) = 0.34 and p = 0.7138, indicate that there is no interaction between the two factors on the difference of forces.

The results for the base force, F(1,15) = 1.5 and p = 0.2392, show that there is no significant difference between the levels of base force, meaning that the base force does not affect the adaptation of our sensory threshold. We adapt equally to forces independent of the base force. The results of ANOVA for the force increment/decrement, F(1,15) = 0.0 ; p = 0.9456, indicate that adaptation affects the upper and lower limens of force threshold equally.

4.5 Conclusions

A haptic-enabled virtual environment is developed to quantify the limitations of human force perception. The thresholds of force perception are measured with respect to the factors such as the base force and force increment/decrement. The effects of the applied forces on the subject accuracy, and the adaptation of the subject's kinesthetic sense to forces are also investigated.

The measured JNDs can be used in the development of HEVEs when the user hand is in motion. For example, a developer may want to simulate two different haptic media in a VE when the user's hand continuously moves in the VE. Based on the results, the haptic display can apply a force such as 0.15 N opposed to the user's hand motion to simulate a high-viscous environment, then decrease the force by at least 0.063 N (0.42×14%) to simulate a lower viscous environment. The user notices the difference between the two environments because the change in force exceeds the threshold of force perception.

The results and analysis of data in Section 4.4.1 show a Weber trend for the measured force JND, indicating that the force JND is significantly large for extremely small base forces and it decreases for the higher base forces.

The JNDs measured in this study are in the extremely small base force region of the Weber's fraction. Thus, the JNDs are very high for the low base force. The results confirm that the JND values in Chapter 3 are also valid because they are measured for a small base force, which is the friction of the haptic device.

Although the upper and lower limens of JND are almost symmetric for the medium and high base forces, they are not symmetric for the low base force. In other words, the user is not equally sensitive to the increment or decrement of applied forces for all base forces.

Time is critical in the development of haptic displays. Thus, time-efficient methods are essentials to measure the required force thresholds. Many psychophysical studies [23] have required long-term experiments to study human perception. For example in [50] each experiment took hours with an average of 2048 trials for one experimental condition. In addition, the adaptation to force is also problematic in very long experimental sessions. In our study, each level of the experiment is completed within roughly a 50-minute session with 48 trials. The IS method takes less time compared to other methods because only a few stimuli values that are far above or below threshold are presented. As a result, a suitable compromise is found between the robust results and time to obtain specific data relevant to the development of haptic-enabled VEs.

The results and analysis in Section 4.4.2 indicate that sub-threshold forces can affect the human performance in haptic-enabled VR applications. Interestingly, forces can change the accuracy even when the subjects are allowed to control their actions through visual feedback. In other words, we can pull/push the user's hand by increasing/decreasing applied forces. Therefore, factors such as the force increment/decrement can be incorporated in the control of users' movements in HEVEs.

The results also show that the index performance and missing error of the Fitts' task cannot show the effects of forces on accuracy. Instead, the difference between the overshoot and undershoot errors can be used as a performance index to quantify user accuracy in the application of forces.

Based on the results in Section 4.4.3, users lose sensitivity to applied forces in a VE when they are using haptic devices for an extended period of time. The results of ANOVA and Figure 4.15 show that if the loss of sensitivity is differentially affected by the base force or force increment/decrement, the effect is relatively small. Thus, the reduction in sensitivity, at the baseline forces at least, is independent of the base force intensity and the force decreasing or increasing.

4.6 Summary of the Results and Hypotheses

This section presents a summary of the results in Section 4.4 in regards to the hypotheses that are tested in this chapter. All hypotheses are confirmed.

H_2: The results show a Weber's trend, which is that the force JND is significantly large for extremely small base forces and it decreases for the higher base forces. This explains why the measured force JNDs in Chapter 3 are larger than the JNDs in the literature.

H_3: The results indicate that the user is not equally sensitive to the increment or decrement of applied forces for all base forces. For example the upper and lower limens of the low base force are not symmetric.

H_4: The results show that sub-threshold forces can affect the human movement accuracy in haptic-enabled virtual environments, indicating that forces can change the accuracy even when the subjects are allowed to control their actions through visual feedback.

H_5: The results indicate that users adapt to applied forces in HEVEs when their hands are in motion. The results also show that the adaptation effect observed in Chapter 3 was not related to the staircase method.

Chapter 5

Conclusions and Future Directions

This thesis reports the results of experimental research designed to investigate the limitations and capabilities of human force perception and motor control when the user's hand moves in a haptic-enabled virtual environment (HEVE). The thresholds of force perception and the accuracy of movement are measured with respect to the factors such as the user's hand velocity, the base force, and force increment/decrement.

The force thresholds or JNDs measured in this study can be used in the haptic display of forces in VEs when the user's hand is in motion. For instance, haptic display developers should apply forces higher than the measured JNDs to ensure the user effectively perceives the haptic effects.

In the application of friction compensation [32], the over-compensation of friction can be problematic because there is an increase in errors even though the user is not aware of the applied forces. Therefore, there is a trade-off in applications. Too much or too little friction compensation can actually make things worse.

The results of the adaptation to forces can assist researchers to design experimental procedures in force perception studies when forces are applied on subjects' hands for a period of time, and the kinesthetic sense is the dominant sense in their study.

The human factors issues that are raised by the results of the experiments may guide future studies. For instance, based on the results, the effect of the base force on the JND of the human force perception is dependent on the force increment/decrement. This indicates that the interaction of these two factors should be taken into consideration in the design of haptic display of VEs.

5.1 Perception-based Compression Techniques

The results of this study have provided a basis for which the integration of the force JNDs in the presence of velocity can be used to transmit compressed haptic data unbeknown to the user. The perception-based compression techniques are explained in detail in Chapter 2. The threshold of human force perception plays a significant role in the development of these techniques. This thesis investigates the impact of important factors on the force threshold that affect these techniques when the user's hand is in motion. These factors include the force direction, base force intensity, force increment/decrement, and velocity of the user's hand. The results show that force JNDs depend on the user's hand velocity, the base force and the force increment/decrement. Thus, these variables must be incorporated in an efficient haptic data compression algorithm when the user's hand is in motion.

5.2 Computer-Aided Design

This thesis studies the effect of forces on the accuracy of movement in a haptic-enabled virtual environment. Forces are applied on subjects' hands while the subjects carry out a multi-modal Fitts' type task. The effects of changes in the base force intensity and the force increment/decrement are investigated using a performance index. The results indicate that factors such as the base force intensity and force increment/decrement can be incorporated in the control of users' movements in HEVEs. In other words, we can pull/push the user's hand by increasing/decreasing the force without the user being aware of it. For example, to improve the accuracy in the task of Figure 1.2, we can precisely adjust the position of the cursor by applying the sub-threshold aid or opposed forces to the designer's hand. Based on the results, the aid forces enable the user to precisely reach the target position. If the cursor (and thus, the designer's hand) is on the target, opposed forces can help him/her to stay on the target position.

The difference of overshoots and undershoots can be used as a performance index to quantify user accuracy in the application of forces. Future work will study the performance indexes for different applications. In addition, the effect of forces on human performance in a 3D task will also be studied.

The force JNDs measured in this study are relatively small. As a result, the intensity of sub-thresholds and the errors are small. In addition, in many applications such as CAD, it may be desired to push/pull the user's hand by stronger forces. Based on the results of the low base force in Chapter 4, the larger the force threshold, the larger the impact on the user accuracy. Thus, if the force threshold were increased, there would be more effective manipulation of the user's hand. Psychophysical methods, which are discussed in this study, are generally conservative. Subjects focused on their sensation because they were asked to identify the JND. However, users do not usually attempt to notice very small changes in applied forces when they work with haptic interfaces. Future work will study factors affecting the user's attention in order to decrease their sensitivity to forces, and, subsequently, increase the intensity of sub-threshold forces in CAD.

Appendices

Appendix A

Results

Subject (Gender)	Force Direction	Low Velocity	Medium Velocity	High Velocity
OO (M)	Increment	22.84	35.8	49.07
LY (F)	Increment	17.29	23.46	32.71
SA (M)	Increment	19.14	25.31	31.79
MT (M)	Increment	16.36	23.77	31.17
MS (M)	Decrement	18.83	23.46	31.17
KB (F)	Decrement	18.21	21.91	27.16
MB (M)	Decrement	16.05	25.00	32.10
ME (M)	Decrement	20.37	34.57	41.36

Table A.1: The force JNDs (%) of backdrive friction force (i.e. base force = 0.27 N) based on force increment/decrement and the subject's hand velocity. The first letter of first and last names of subjects are used to refer to subjects. (Female: F; Male: M)

Subject	Base Force Intensity					
(Gender)	Low (0.12 N)		Medium (0.42 N)		High (0.77 N)	
	Inc	Dec	Inc	Dec	Inc	Dec
FF (F)	50	36.11	7.94	20	6.1	10.82
VM (F)	48.15	15.83	7.69	10.95	10.78	15.96
HS (F)	61.11	20.37	9.52	18.52	14.68	8.16
XW (F)	88.89	67.71	25.89	15.87	4.13	11.93
NJ (F)	108.33	43.75	25.13	13.85	7.14	14.47
XB (F)	46.88	20.14	8.33	11.56	8.98	4.62
FP (F)	98.61	67.59	22.02	13.76	11.91	15.03
XY (F)	63.19	46.43	15.98	4.93	8.09	4.07
MZ (M)	34.73	50.93	10.07	11.01	6.49	11.69
BB (M)	50	67.59	15.47	9.72	3.67	15.8
RV (M)	68.51	41.03	20.35	16.67	9.48	8.08
AG (M)	70.83	47.5	20.15	10.71	12.99	10.61
JA (M)	34.03	51.19	10.61	13.92	10.71	6.49
AK (M)	63.54	31.25	18.05	8.5	11.91	9.25
YF (M)	49.08	27.5	9.3	13.76	10.17	11.3
CZ (M)	90.92	62.97	26.9	12.38	17.44	13.56

Table A.2: The force JNDs (%) for all levels of the base force intensity and force increment/decrement. The first letter of first and last names of subjects are used to refer to subjects. (Female: F; Male: M; Force Increment: Inc, Force Decrement: Dec)

Subject	Base	Force	Before Force Inc/Dec			After Force Inc/Dec		
(Gender)	Force	Inc/Dec	OS	US	Hit	OS	US	Hit
FF (F)	Low	Inc.	5.31	0.53	27.31	2.34	2.60	27.45
FF (F)	Low	Dec.	3.91	1.04	28	5.59	1.60	26.85
FF (F)	Medium	Inc.	4.67	2.60	27.38	3.39	1.56	28.08
FF (F)	Medium	Dec.	4.66	2.88	27.8	3.61	1.35	28.07
FF (F)	High	Inc.	6.96	0.77	25.57	7.85	0.51	25.86
FF (F)	High	Dec.	7.03	0.52	25.36	10.21	0.26	24.43
VM (F)	Low	Inc.	5.39	2.81	28	3.08	4.27	27.93
VM (F)	Low	Dec.	4.49	2.99	28.09	3.96	3.05	27.73
VM (F)	Medium	Inc.	2.85	3.48	26.91	0.64	2.24	27.55
VM (F)	Medium	Dec.	1.75	3.25	27.14	2.28	3.30	26.57
VM (F)	High	Inc.	2.96	3.16	29.69	3.27	3.48	28.5
VM (F)	High	Dec.	3.36	2.24	29.71	1.53	3.44	29.24
HS (F)	Low	Inc.	3.74	0.98	25.48	3.55	3.39	25.04
HS (F)	Low	Dec.	6.10	0.68	25	3.02	1.01	26
HS (F)	Medium	Inc.	5.04	0.56	25.92	5.59	1.40	25.62
HS (F)	Medium	Dec.	3.33	1.39	26.38	5.22	0.82	26.31
HS (F)	High	Inc.	5.06	1.56	26.67	4.72	1.57	26.5
HS (F)	High	Dec.	4.23	1.37	26.5	6.94	1.79	25.5
XB (F)	Low	Inc.	3.97	2.48	29	1.74	1.99	29.77
XB (F)	Low	Dec.	4.93	1.92	28.33	4.30	0.27	29.58
XB (F)	Medium	Inc.	2.77	1.01	29.38	2.00	1.75	29.62
XB (F)	Medium	Dec.	4.25	2.36	28.29	4.72	1.65	28.36
XB (F)	High	Inc.	1.54	0.88	29.6	1.1	0.88	29.8
XB (F)	High	Dec.	3.14	0.97	28.36	0.95	1.43	29.28

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Subject (Gender)	Base Force	Force Inc/Dec	Before Force Inc/Dec			After Force Inc/Dec		
			OS	US	Hit	OS	US	Hit
NJ (F)	Low	Inc.	1.28	0.91	28.16	1.50	2.63	26.89
NJ (F)	Low	Dec.	2.22	0.99	28	1.76	1.51	27.5
NJ (F)	Medium	Inc.	3.28	1.43	29.06	1.66	1.45	29.25
NJ (F)	Medium	Dec.	3.02	1.76	29.08	4.08	1.02	28.62
NJ (F)	High	Inc.	1.51	1.72	26.47	1.31	1.53	26.18
NJ (F)	High	Dec.	1.93	0.86	26.71	1.09	0.88	26.35
XW (F)	Low	Inc.	1.67	2.60	30.35	1.12	1.12	30.76
XW (F)	Low	Dec.	0.99	1.26	27.67	2.15	0.27	27.89
XW (F)	Medium	Inc.	0.89	2.32	28.58	1.44	2.34	28.11
XW (F)	Medium	Dec.	1.12	1.57	28.93	1.12	1.57	29.00
XW (F)	High	Inc.	1.76	0.59	31.67	0.29	2.20	31.71
XW (F)	High	Dec.	0.95	0.95	32.19	0.38	0.76	32.56
FP (F)	Low	Inc.	4.33	1.65	26.76	1.65	2.89	27.24
FP (F)	Low	Dec.	5.96	1.54	26.18	5.78	1.07	27.19
FP (F)	Medium	Inc.	7.05	2.14	25	3.43	3.22	25.59
FP (F)	Medium	Dec.	5.71	1.77	26.11	10.44	1.93	25.17
FP (F)	High	Inc.	6.02	0.43	27.19	5.81	1.94	26.81
FP (F)	High	Dec.	4.87	1.04	27.05	5.71	0.67	27.85
XY (F)	Low	Inc.	2.18	1.63	29.44	0.37	4.94	28.78
XY (F)	Low	Dec.	3.47	1.95	29.07	1.75	3.06	29.07
XY (F)	Medium	Inc.	0.87	0.66	30.07	1.10	3.09	28.93
XY (F)	Medium	Dec.	1.62	1.85	29.79	0.95	3.10	28.71
XY (F)	High	Inc.	1.33	2.67	30.86	0.66	4.41	30.79
XY (F)	High	Dec.	0.69	2.97	30.07	1.15	5.28	29.14

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Subject	Base	Force	Before Force Inc/Dec			After Force Inc/Dec		
(Gender)	Force	Inc/Dec	OS	US	Hit	OS	US	Hit
MZ (M)	Low	Inc.	4.67	1.92	28.33	6.27	2.72	27.83
MZ (M)	Low	Dec.	3.73	1.63	29	5.16	2.11	28.21
MZ (M)	Medium	Inc.	4.21	0.79	30.08	3.97	1.06	29.92
MZ (M)	Medium	Dec.	3.95	0.79	30.13	9.56	2.39	27.63
MZ (M)	High	Inc.	3.94	1.72	29.46	3.18	1.96	29.85
MZ (M)	High	Dec.	4.27	1.30	29.94	5.96	0.37	29.59
BB (M)	Low	Inc.	3.16	1.05	28	0.80	2.13	28.08
BB (M)	Low	Dec.	2.33	1.27	28.5	3.77	1.89	28.13
BB (M)	Medium	Inc.	3.10	1.11	28.87	2.64	2.64	28.67
BB (M)	Medium	Dec.	3.16	2.68	27.64	2.89	4.34	27.50
BB (M)	High	Inc.	0.46	1.39	28.33	2.07	1.84	27.80
BB (M)	High	Dec.	1.32	2.08	28.44	4.81	2.31	26.83
AK (M)	Low	Inc.	4.84	1.69	25.73	3.36	3.36	25.93
AK (M)	Low	Dec.	4.16	3.42	27	6.70	5.02	26.35
AK (M)	Medium	Inc.	5.39	2.12	26.67	4.44	2.51	26.78
AK (M)	Medium	Dec.	4.13	1.81	28	5.80	2.37	26.77
AK (M)	High	Inc.	9.01	0.86	24.71	7.54	2.22	23.94
AK (M)	High	Dec.	5.19	1.35	25.88	7.76	1.18	24.19
JA (M)	Low	Inc.	4.71	2.69	29.5	3.96	3.74	29.93
JA (M)	Low	Dec.	2.08	3.54	30.20	3.33	2.08	30.33
JA (M)	Medium	Inc.	3.51	4.17	30.07	1.54	3.73	30.86
JA (M)	Medium	Dec.	2.19	2.68	30.08	2.92	4.14	29.38
JA (M)	High	Inc.	1.08	1.52	29.93	1.1	1.32	29.60
JA (M)	High	Dec.	1.25	1.50	29.93	1.02	0.51	29.69

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Subject	Base	Force	Before Force Inc/Dec			After Force Inc/Dec		
(Gender)	Force	Inc/Dec	OS	US	Hit	OS	US	Hit
RV (M)	Low	Inc.	6.94	1.91	25.4	6.43	3.81	25.13
RV (M)	Low	Dec.	5.43	2.36	26	6.76	2.90	24.93
RV (M)	Medium	Inc.	4.59	2.09	26.29	4.26	1.71	25.94
RV (M)	Medium	Dec.	6.25	1.56	25.29	5.04	1.86	25.07
RV (M)	High	Inc.	2.77	2.34	27.88	2.77	2.77	27.69
RV (M)	High	Dec.	4.18	2.70	27.07	2.22	1.97	27.79
AG (M)	Low	Inc.	3.02	1.26	29.23	0.62	2.67	29.38
AG (M)	Low	Dec.	2.52	2.27	29.08	3.50	1.17	29.21
AG (M)	Medium	Inc.	2.52	2.27	29.08	6.99	0.24	25.67
AG (M)	Medium	Dec.	4.08	2.36	29.07	3.36	4.47	29.43
AG (M)	High	Inc.	1.70	2.27	29.82	1.15	3.65	29.18
AG (M)	High	Dec.	2.20	2.40	29.88	2.45	1.64	29.31
YF (M)	Low	Inc.	4.26	2.96	27.83	4.84	7.64	26.11
YF (M)	Low	Dec.	5.14	1.71	27.19	8.33	2.99	25.94
YF (M)	Medium	Inc.	2.50	4.62	28.35	3.11	5.84	27.53
YF (M)	Medium	Dec.	2.53	6.06	27.85	3.07	6.65	27.15
YF (M)	High	Inc.	4.44	4.65	27.63	4.03	4.24	27.69
YF (M)	High	Dec.	5.99	2.69	28.67	5.97	2.88	28.87
CZ (M)	Low	Inc.	4.36	2.26	25	2.81	3.47	24.89
CZ (M)	Low	Dec.	4.42	2.41	27.3	3.78	2.19	27.76
CZ (M)	Medium	Inc.	4.28	0.86	27.7	5.75	4.27	27.4
CZ (M)	Medium	Dec.	4.38	2.41	28.4	6.81	0.64	29
CZ (M)	High	Inc.	3.79	1.81	27.53	2.18	1.81	27.79
CZ (M)	High	Dec.	3.41	3.61	27.29	3.22	2.41	27.59

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Subject	Base	Force	Before Force Inc/Dec			After Force Inc/Dec		
(Gender)	Force	Inc/Dec	OS	US	Hit	OS	US	Hit

Table A.3: The average number of overshoots (OS), undershoots (US), and hits (Hit) in *unnoticed* trials for each subject and all levels of the two factors: the base force intensity and force increment/decrement (inc/dec).

Subject	Base	Force	Before Force Inc/Dec			After Force Inc/Dec		
(Gender)	Force	Inc/Dec	OS	US	Hit	OS	US	Hit
FF (F)	Low	Inc.	5.14	1.51	28.09	4.66	1.55	27.45
FF (F)	Low	Dec.	5.83	0.62	27.73	6.27	0.94	26.91
FF (F)	Medium	Inc.	3.49	3.17	26.73	1.94	3.24	26.64
FF (F)	Medium	Dec.	3.23	0.81	26.44	5.44	0.78	26.78
FF (F)	High	Inc.	4.82	0.44	26.4	5.60	1.29	25.5
FF (F)	High	Dec.	5.14	0.57	26.8	9.50	1.68	26.1
VM (F)	Low	Inc.	4.29	4.62	27.6	2.40	6.51	26.6
VM (F)	Low	Dec.	2.51	3.76	28.77	5.03	3.02	28.15
VM (F)	Medium	Inc.	1.37	3.84	26.62	2.53	3.37	25.78
VM (F)	Medium	Dec.	3.07	2.73	27.6	1.03	2.06	28.2
VM (F)	High	Inc.	1.17	2.33	31	2.54	2.97	27.88
VM (F)	High	Dec.	2.26	1.36	30.43	1.34	6.70	29.43
HS (F)	Low	Inc.	1.58	1.58	26.29	3.74	1.60	25.29
HS (F)	Low	Dec.	5.40	1.99	25.08	5.40	1.14	25.31
HS (F)	Medium	Inc.	3.04	1.11	26.69	3.54	1.91	26.69

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Subject	Base	Force	Before Force Inc/Dec			After Force Inc/Dec		
(Gender)	Force	Inc/Dec	OS	US	Hit	OS	US	Hit
HS (F)	Medium	Dec.	5.33	0.33	25.73	5.96	2.32	25.18
HS (F)	High	Inc.	4.71	0.59	26.83	5.88	0	26.67
HS (F)	High	Dec.	7.55	0.72	25.5	8.33	1.45	24.9
XB (F)	Low	Inc.	4.60	1.44	29.73	1.47	2.93	29.64
XB (F)	Low	Dec.	2.30	1.46	26.31	3.36	0.76	26.88
XB (F)	Medium	Inc.	4.42	1.77	28.91	1.48	3.25	29.27
XB (F)	Medium	Dec.	1.60	1.28	30.30	3.15	3.15	29.7
XB (F)	High	Inc.	3.33	1.11	28.67	1.14	0.38	28.89
XB (F)	High	Dec.	1.72	1.38	28.1	0.33	1.33	29.6
NJ (F)	Low	Inc.	2.86	1.43	26.8	0.74	2.21	26.4
NJ (F)	Low	Dec.	1.75	0.70	27.9	2.11	1.06	27.5
NJ (F)	Medium	Inc.	4.51	0.41	29	3.78	0.00	28.63
NJ (F)	Medium	Dec.	3.52	2.35	29.18	4.55	0.00	28.64
NJ (F)	High	Inc.	1.05	0.53	26.71	1.08	1.08	26
NJ (F)	High	Dec.	1.05	1.57	26.57	2.63	2.63	25.71
XW (F)	Low	Inc.	1.82	0.91	30.57	0.45	2.71	30.57
XW (F)	Low	Dec.	2.78	0.79	30.38	2.33	0.39	31.38
XW (F)	Medium	Inc.	0.00	1.92	29.14	0.00	3.85	28.57
XW (F)	Medium	Dec.	1.52	2.27	28.22	0.75	1.12	29.11
XW (F)	High	Inc.	0.44	1.31	32.14	0.91	1.36	30.86
XW (F)	High	Dec.	1.90	1.14	31.88	1.54	0.77	31.75
FP (F)	Low	Inc.	5.45	1.49	26.86	3.48	1.49	27.29
FP (F)	Low	Dec.	4.91	0.70	26.9	6.27	1.04	26.6
FP (F)	Medium	Inc.	7.29	0.52	25.29	5.18	1.04	25.86

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Subject	Base	Force	Before Force Inc/Dec			After Force Inc/Dec		
(Gender)	Force	Inc/Dec	OS	US	Hit	OS	US	Hit
FP (F)	Medium	Dec.	4.89	0.44	26.63	9.21	1.32	25.5
FP (F)	High	Inc.	4.82	0.44	27	5.60	1.29	27
FP (F)	High	Dec.	5.14	0.57	27.5	9.50	1.68	26.5
XY (F)	Low	Inc.	1.02	1.36	28.8	0.68	3.04	28.5
XY (F)	Low	Dec.	1.23	3.08	28.27	1.54	0.93	28.73
XY (F)	Medium	Inc.	1.18	0.88	30.18	1.75	3.21	29.64
XY (F)	Medium	Dec.	1.34	4.30	29.25	1.36	3.00	29.25
XY (F)	High	Inc.	0.63	2.85	30.5	0	7.67	28.9
XY (F)	High	Dec.	1.41	3.39	30.64	1.15	4.87	29.82
MZ (M)	Low	Inc.	6.01	1.20	28.09	5.04	1.19	28.73
MZ (M)	Low	Dec.	2.98	2.32	28.6	6.37	0.96	29.1
MZ (M)	Medium	Inc.	5.29	0.53	29.67	5.71	1.30	29.83
MZ (M)	Medium	Dec.	3.60	0.80	29.88	4.71	1.96	29.75
MZ (M)	High	Inc.	5.83	0.87	29.09	3.45	0.86	30.27
MZ (M)	High	Dec.	5.96	0.46	29.14	8.48	0	29.29
BB (M)	Low	Inc.	2.46	2.19	29.08	1.10	2.74	29.25
BB (M)	Low	Dec.	2.95	0.84	28.5	5.33	2.46	28.13
BB (M)	Medium	Inc.	3.72	2.23	28.11	1.13	1.50	28.87
BB (M)	Medium	Dec.	2.23	2.23	28.58	1.63	3.25	29.25
BB (M)	High	Inc.	2.83	2.83	27.27	3.24	0.97	26.91
BB (M)	High	Dec.	1.69	0.57	28.83	3.39	1.13	28.17
AK (M)	Low	Inc.	3.85	1.54	27.33	4.60	7.66	25.44
AK (M)	Low	Dec.	4.17	1.39	27.2	8.53	0.68	26.6
AK (M)	Medium	Inc.	3.77	2.51	28	9.79	3.40	25.5

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Subject	Base	Force	Before Force Inc/Dec			After Force Inc/Dec		
(Gender)	Force	Inc/Dec	OS	US	Hit	OS	US	Hit
AK (M)	Medium	Dec.	6.96	2.22	26.09	6.62	3.47	25.9
AK (M)	High	Inc.	8.90	0.00	24.86	7.07	0	24.43
AK (M)	High	Dec.	7.04	0.94	24.5	4.21	1.87	25.13
JA (M)	Low	Inc.	4.11	2.85	29.4	1.56	4.98	30
JA (M)	Low	Dec.	2.79	3.48	29.89	3.46	1.73	30.44
JA (M)	Medium	Inc.	0.93	3.41	30.9	1.88	5.02	29.7
JA (M)	Medium	Dec.	2.31	4.32	29.45	1.98	1.41	31.09
JA (M)	High	Inc.	1.81	1.45	29.67	0.37	2.21	29.33
JA (M)	High	Dec.	1.45	2.31	30.27	2.31	2.02	30.18
RV (M)	Low	Inc.	5.79	3.09	26.22	2.77	4.74	26
RV (M)	Low	Dec.	5.08	3.52	26	11.34	3.24	23.44
RV (M)	Medium	Inc.	6.74	1.55	25.29	2.65	1.06	26
RV (M)	Medium	Dec.	4.71	1.45	25.9	7.69	2.20	24.6
RV (M)	High	Inc.	2.21	2.65	26.88	1.80	5.41	25.75
RV (M)	High	Dec.	2.47	3.53	26.6	3.90	2.13	26.5
AG (M)	Low	Inc.	5.07	1.19	28.55	0.83	4.15	28.63
AG (M)	Low	Dec.	0.89	4.17	29	2.61	2.29	29.1
AG (M)	Medium	Inc.	4.22	0.90	28.64	7.11	1.19	28.78
AG (M)	Medium	Dec.	2.14	2.14	29.89	4.38	2.84	30
AG (M)	High	Inc.	1.75	3.06	31.14	0.92	4.15	29.43
AG (M)	High	Dec.	2.71	4.26	30	0.40	2.39	30.5
YF (M)	Low	Inc.	2.96	2.55	27.25	2.98	2.55	27.75
YF (M)	Low	Dec.	5.90	2.80	26.73	3.99	1.53	28
YF (M)	Medium	Inc.	1.27	4.30	28.69	1.77	3.29	28.85

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Subject (Gender)	Base Force	Force Inc/Dec	Before Force Inc/Dec			After Force Inc/Dec		
			OS	US	Hit	OS	US	Hit
YF (M)	Medium	Dec.	2.33	3.79	29.27	2.39	2.39	29
YF (M)	High	Inc.	4.54	2.10	29.67	3.57	2.5	29.22
YF (M)	High	Dec.	4.13	2.89	28.13	2.76	4.33	29.5
CZ (M)	Low	Inc.	5.69	4.27	27.14	2.00	3.00	27.14
CZ (M)	Low	Dec.	7.43	1.49	26.29	3.15	1.80	30.14
CZ (M)	Medium	Inc.	4.82	2.41	28.88	8.20	4.01	26.75
CZ (M)	Medium	Dec.	4.17	1.52	27.67	5.86	2.07	29.67
CZ (M)	High	Inc.	3.31	3.31	28.2	2.86	4.29	26
CZ (M)	High	Dec.	3.37	1.44	28.29	5.74	2.87	27.29

Table A.4: The average number of overshoots (OS), undershoots (US), and hits (Hit) in *noticed* trials for each subject and all levels of the two factors: the base force intensity and force increment/decrement (inc/dec).

Base force Intensity	Force Inc/Dec	IP before force Inc/Dec	IP after force Inc/Dec	ME before force Inc/Dec	ME after force Inc/Dec
Low	Inc.	6.95 ± 0.14	6.95 ± 0.13	5.82 ± 0.44	6.11 ± .70
Low	Dec.	6.99 ± 0.10	6.92 ± 0.13	5.80 ± 0.42	6.36 ± 0.67
Medium	Inc.	7.08 ± 0.12	6.97 ± 0.13	5.61 ± 0.49	5.69 ± 0.51
Medium	Dec.	7.10 ± 0.10	6.92 ± 0.12	5.83 ± 0.41	7.09 ± 0.65
High	Inc.	7.20 ± 0.14	7.13 ± 0.15	5.17 ± 0.61	5.34 ± 0.59
High	Dec.	7.15 ± 0.14	6.98 ± 0.17	5.16 ± 0.48	5.57 ± 0.72

Table A.5: The average IP and missing error (ME) and standard errors for unnoticed data across all subjects.

Base force Intensity	Force Inc./Dec.	F1 (N)	F2 (N)
Low	Increment	0.073 ± 0.0058	0.092 ± 0.0084
Low	Decrement	0.054 ± 0.004	0.069 ± 0.0094
Medium	Increment	0.063 ± 0.0068	0.08 ± 0.0091
Medium	Decrement	0.052 ± 0.0053	0.068 ± 0.0048
High	Increment	0.076 ± 0.0058	0.098 ± 0.0084
High	Decrement	0.076 ± 0.0075	0.104 ± 0.0082
Mean		0.066 ± 0.0026	0.085 ± 0.0035

Table A.6: The average of forces and standard errors for adaptation.

Appendix B

ANOVA Tables

Significant p-values are presented in bold face in all ANOVA tables.

Source	DF	Sum of Squares	Mean Square	F value	p Value
Main Effects					
velocity	2	1015.5	507.75	56.75	$<$ **0.0001**
Error(velocity*subj(force inc/dec))	12	107.36	8.95		
force inc/dec	1	14.29	14.29	0.19	0.6804
Error(subj(force inc/dec))	6	458.33	76.39		
Two-way Interaction					
velocity*force inc/dec	2	8.73	4.36	0.49	0.6257
Error(velocity*subj(force inc/dec))	12	107.36	8.95		

Table B.1: ANOVA table for two-way ANOVA on the JND data in Figures 3.9 and 3.10. The velocity and force increment/decrement are independent variables.

Source	DF	Sum of Squares	Mean Square	F value	p Value
Main Effects					
base force	2	37218.83	18609.41	119.91	$<$ **0.0001**
Error(subj*base force)	30	4655.9	155.2		
force inc/dec	1	1343.05	1343.05	11.68	**0.0038**
Error(subj*force inc/dec))	15	1724.13	114.94		
Two-way Interaction					
base force*force inc/dec	2	2116.89	1058.44	12.28	**0.0001**
Error(subj*base force*force inc/dec)	30	25.85.89	86.20		

Table B.2: ANOVA table for two-way ANOVA on the JND data in Figure 4.6. The base force intensity and force increment/decrement are independent variables. The analysis is conducted for three levels of the base force intensity, including low, medium, and high.

Source	DF	Sum of Squares	Mean Square	F value	p Value
Main Effects					
base force	2	0.3588	0.1794	1.53	0.2330
Error(subj*base force)	30	3.5176	0.1173		
force inc/dec	1	0.0123	0.0123	0.68	0.4226
Error(subj*force inc/dec))	15	0.2707	0.0180		
Two-way Interaction					
base force*force inc/dec	2	0.0066	0.0033	0.27	0.7650
Error(subj*base force*force inc/dec)	30	0.3644	0.0121		

Table B.3: The ANOVA table for two-way ANOVA on the IP before force increment/decrement. The base force intensity and force increment/decrement are independent variables.

Source	DF	Sum of Squares	Mean Square	F value	p Value
Main Effects					
base force	2	12.01	6.0499	2.32	0.1153
Error(subj*base force)	30	78.11	2.604		
force inc/dec	1	0.0213	0.0213	0.01	0.9373
Error(subj*force inc/dec))	15	50.01	3.33		
Two-way Interaction					
base force*force inc/dec	2	1.0531	0.5266	0.51	0.6080
Error(subj*base force*force inc/dec)	30	31.23	1.04		

Table B.4: The ANOVA table for two-way ANOVA on the missing error before force increment/decrement. The base force intensity and force increment/decrement are independent variables.

Source	DF	Sum of Squares	Mean Square	F value	p Value
Main Effects					
base force	2	0.20	0.10	1.2	0.3167
Error(subj*base force)	30	2.57	0.09		
force inc/dec	1	0.13	0.13	1.15	0.3010
Error(subj*force inc/dec))	15	1.70	0.11		
Two-way Interaction					
base force*force inc/dec	2	0.009	0.005	0.1	0.9075
Error(subj*base force*force inc/dec)	30	1.42	0.47		

Table B.5: The ANOVA table for a two-way ANOVA on the difference between the IPs of before and after force inc/dec for unnoticed data in Figure 4.8. The base force intensity and force increment/decrement are independent variables.

Source	DF	Sum of Squares	Mean Square	F value	p Value
Main Effects					
base force	2	2.36	1.18	0.36	0.7576
Error(subj*base force)	30	126.41	4.21		
force inc/dec	1	7.67	7.67	2.52	0.1331
Error(subj*force inc/dec))	15	45.59	3.04		
Two-way Interaction					
base force*force inc/dec	2	2.28	2.58	0.72	0.4966
Error(subj*base force*force inc/dec)	30	95.58	3.19		

Table B.6: The ANOVA table for a two-way ANOVA on the difference between the missing errors of before and after force inc/dec for unnoticed data in Figure 4.9. The base force intensity and force increment/decrement are independent variables.

Source	DF	Sum of Squares	Mean Square	F value	p Value
Main Effects					
base force	2	24.01	12.01	4.19	**0.0249**
Error(subj*base force)	30	85.97	2.87		
force inc/dec	1	94.23	94.23	27.49	$<$ **0.0001**
Error(subj*force inc/dec))	15	51.41	3.43		
Two-way Interaction					
base force*force inc/dec	2	15.74	7.87	1.70	0.2004
Error(subj*base force*force inc/dec)	30	139.17	4.64		

Table B.7: The ANOVA table for a two-way ANOVA on the (OS-US)% for *unnoticed* data in Table 4.3 and Figure 4.10. The base force intensity and force increment/decrement are independent variables.

Alpha	0.05
Error Degrees of Freedom	30
Error Mean Square	2.865825
Critical Value of Studentized Range	3.48651
Minimum Significant Difference	1.0434

Tukey Grouping	Mean	N	base
A	-0.0334	32	Medium
A			
B A	-0.1612	32	High
B			
B	-1.1525	32	Low

Table B.8: The results of Tukey test on Δ(OS-US)% in Table 4.3. Means with the same letter are not significantly different.

Source	DF	Sum of Squares	Mean Square	F value	p Value
Main Effects					
base force	2	11.41	5.71	1.19	0.3181
Error(subj*base force)	30	143.83	4.79		
force inc/dec	1	121.52	121.52	13.37	**0.0023**
Error(subj*force inc/dec))	15	136.30	9.08		
Two-way Interaction					
base force*force inc/dec	2	58.82	29.41	5.33	**0.0104**
Error(subj*base force*force inc/dec)	30	165.45	5.52		

Table B.9: The ANOVA table for a two-way ANOVA on the (OS-US)% for *noticed* data in Table 4.4 and Figure 4.12. The base force intensity and force increment/decrement are independent variables.

Source	DF	Sum of Squares	Mean Square	F value	p Value
force	1	0.018	0.018	19.95	**0.0005**
Error(subj*force)	15	0.0135	0.0009		

Table B.10: The ANOVA table for one-way ANOVA on the difference of forces in Figure 4.14.

Source	DF	Sum of Squares	Mean Square	F value	p Value
Main Effects					
base Force	2	1525.00	762.5	1.5	0.2392
Error(subj*base force)	30	15241.67	508.06		
force inc/dec	1	4.17	4.17	0.0	0.9456
Error(subj*force inc/dec))	15	12995.83	866.39		
Two-way Interaction					
base force*force inc/dec	2	433.33	216.67	0.34	0.7138
Error(subj*base force*force inc/dec)	30	19066.67	635.56		

Table B.11: The ANOVA table for a two-way ANOVA on the difference of two forces in Figure 4.15. The base force intensity and force increment/decrement are independent variables.

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