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HUMAN FACTORS FOR DESIGNING A HAPTIC INTERFACE FOR INTERACTION WITH A VIRTUAL ENVIRONMENT

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Abstract – *Designing haptic displays is one of the main challenges in creating virtual reality systems with the sense of touch. The design of the hardware and software of haptic interfaces depends critically on the capabilities of the human haptic system. For example, force feedback interfaces, due to inherent hardware limitations such as friction and actuator saturation, present forces to users in the case of interactions with a virtual environment which are only approximations of the forces that they would feel if they were interacting with the real world. Thus, quantitative human studies are required to obtain the impact on human performance of these approximations in the forces from the haptic devices. First, the focus of this paper is on the quantitative measures of human factors (force thresholds) that affect the design specifications of force feedback haptic interfaces when the human user or the object are in relative motion. Second, the effects of two direction of forces and the increment/decrement of forces are also studied through two experiments. It appears that the JNDs of human force perception depend on the force direction and the force increment/decrement, and these two variables must be incorporated in an efficient haptic design technique when the user's hand is in motion.*

Keywords – *Human factors, haptic, JND, interface design, psychophysics, force, limen, threshold.*

I. INTRODUCTION

Realistic haptic rendering is one of the major technical challenges in the field of virtual reality and haptic displays. The capabilities of the human haptic system play an important role in designing haptic displays. Thus, quantitative human studies are required to obtain the impact of human factors on the design of haptic devices [1]. In this study, a virtual environment is used to derive Just Noticeable Differences (JND) for human force sensing. The 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 direction of stimuli increment called *upper limen*, and the JND in the direction of stimuli decrement called *lower limen* [2]. In this study, two experiments are conducted to determine the force JND of the human haptic system when the human user or the object are in relative motion. In both experiments, JNDs of force sensitivity are obtained for a user engaged in a task that is similar to Fitt's task [3] in a virtual environment. The effects of force direction and the increment/decrement of the forces on force JND are also studied.

II. RELATED WORK

Many researchers have derived JNDs for forces using different kinds of force-feedback devices. Jones [4], in a force matching experiment about the 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. [5] found a JND that lies between 5% and 10% for pinching motions between the finger and thumb with a constant resisting force over a range of different base force values between 2.5 and 10 N. Recently, Allin et al. [6] used the PHANToM^{TM} haptic device to measure a JND force in a virtual environment. Their goal is to use the thresholds of force sensitivity to construct therapeutic force feedback distortions that stay below these thresholds. They focus on JNDs as applied to the index finger, and their results show an average JND of approximately 10% over a number of subjects with a constant base force at 2.25 N. They conclude that the visual feedback distortions in a virtual environment can be created to encourage increased force productions by up to 10%, without a patient's awareness. Lawrence et al. [7] proposed a procedure for measuring the human perception of friction inherent in a haptic interface rather than the friction rendered virtually by a haptic interface. They developed a haptic system where the impedance of the interface such as the inertia, friction and compliance was transparent to the user. They focused on perceptual transparency because true physical transparency was not possible. To achieve the perceptual transparency of friction, they found the threshold below which humans can no longer perceive the presence of friction. Then, they carefully designed the interface with the aid of a friction-reducing controller. The friction was below the requisite threshold in the constructed interface.

Most researchers study the haptic display of stationary rigid

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objects in interaction with the operator's hand. However, motion is important in many virtual reality applications. For example, when a user is immersed in a high-viscous virtual environment (e.g. a bucket of oil), the haptic display must generate forces that are proportional to the velocity of the user's hand motion. The dependence on velocity is observed when a user is sliding on the surface of a virtual object or is in contact with a moving object. Another application 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. In all these applications, unlike previous research, the motion of a user's hand and the virtual haptic object is important.

Lederman et al. [8] investigated the effects of the speed of the relative motion on perceived roughness via a rigid probe. They conducted a variety of experiments based on the mode of touch (active or passive) and different ranges of velocities. They found the effects are multiple and complex. Their results show that increasing speed tended to render surfaces as smoother. However, they also found 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. Our research also focuses on the effects of the speed of the relative velocity on the human haptic perception. However, we are interested in detecting the limitations of the haptic perception in the haptic rendering of virtual environments. In other words, Lederman et al. [8] deals with real textured surfaces via a rigid probe. However, our study focuses on the detection of force thresholds in a virtual environment using a PHANToM^{TM} haptic device. These forces are very small and will be determined through a psychophysics detection method. On the other hand, Lederman et al. studied the effect of inter-element spacing on perceived roughness whereas our study that does not focus on any inter-element spacing effect.

Jandura and Srinivasan [9] analyzed human torque control on a haptic device. They asked participants to maintain a constant angular velocity, while they are applying a constant torque. They found that the JND for torque was 12.7% when the reference torque was 60 mN-m. Similar to our work, they are also interested in the speed of a user's hand motion. However, their focus is on the JND for slow twisting motions while our work is for a broader range of motions.

Zadeh et. al [10] determined the force thresholds of the human haptic system for application to a psychophysically motivated lossy haptic (force) compression technique. They focused on applications where the human user or the object are in relative motion, and presented an approach to measure the Absolute Force Threshold (AFT) based on the velocity of the user's hand motion. The AFTs were detected for three different ranges of velocity of the user's hand motion. They found that, when a user's hand is in motion, fewer haptic details are required to be stored, calculated or transmitted. However, in this paper, the focus is on the differential force threshold (JND) for different force direction and the increment/decrement of the applied forces.

The force JND of human haptic system is determined for different intensities of base force in [4] and [5]. Different studies reported different JNDs for different base force intensities. In this paper, in addition to measuring force JNDs for a base force value (150 mN), a comparative study is also conducted to see if there is any potential effects of force direction on the force JNDs with repect to changes in the increment/decrement of forces.

The result in [8] [9] [10] shows a significant variation in the human perception and the force thresholds while the velocity of the subject's hand is changed, albeit in a different scenario than is studied in this paper. Therefore, our attention is directed to the force thresholds for a user's hand in motion.

Most of these reviewed works study the force JND in the case of an increment in the base force intensity. However, the force JND when a decrement in the base force intensity occurs is also important. For example, a user can slide on the surface of a virtual object with different stiffness via a haptic device. Force feedbacks that are applied to the user's hand may increase or decrease when the user's hand slides over different parts of the object surface.

The remainder of this paper is organized as follows. In Section III, methodologies from the field of psychophysics that are utilized to measure the force thresholds are introduced. The psychophysical experiments, the results, and the possible sources of errors are presented and discussed in Section IV and Section V, respectively. Finally, the conclusions and future studies are presented in Section VI.

III. PSYCHOPHYSICS STANDARD METHODS FOR MEASURING THRESHOLDS

Psychophysics mostly deals with detecting absolute and differential thresholds (JND) of perception as well as their variations with respect to other aspects of the sensory stimuli, such as frequency or intensity level [2]. There are many methods to determine the absolute and differential thresholds. According to [2], the method of *limits* is one the most well known methods for detecting absolute and differential thresholds.

A. *Method of limits*

In the method of limits, 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 the 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 threshold is the average of the transition points over all of the series. The main advantage of this technique is that it is not time-consuming.

A number of errors are related to 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 these errors are called *errors of habituation*. On the contrary, sometimes observers might falsely expect the arrival of the stimulus at their threshold, and keep reporting that the change has happened. This error is called the *error of expectation*. However, 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.

B. *Interweaving staircase method*

The *staircase* method is a modification of the method of limits for detecting 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. Therefore, 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. However, its sources of biases are the same as the method of limits [2].

The Interweaving Staircase (IS) [11] method is a variation of staircase method that is used to measure the JND in the direction of force increment and in the direction of force decrement. In the middle of each trial, when the subject's hand speed is within the desirable speed range, the experimenter randomly increments/decrements the continuous applied base force. In IS method, the experimenter starts by presenting a sequence of forces (the base force plus the increment/decrement) which progressively increases or decreases in value. The subject responds with Yes or No to detecting changes in force value. When the subject's response changes from one or a series of the same response (e.g. No, No, No) to the other response (e.g. Yes), 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 IS method is to reduce the possible biases compared to the original staircase method. In IS method, a subject has to report one of the three possible responses (increment, decrement, 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 (ascending or descending).

IV. METHODS

A. *Participants*

There were 6 participants. All were between the ages of 25 and 39. All were regular computer users and students at the University of Waterloo. They were right-handed, and had no more than trivial previous exposures 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 \$10 for their participation in each session. The experiment was conducted in accordance with the University of Waterloo ethical guidelines.

B. *Apparatus and Material*

In all experiments, JNDs of force sensitivity is determined for a user engaged in a task that is similar to Fitt's task [3] in

Fig. 1. The experimental setup: the PHANToM^{TM} haptic device and a subject.

a virtual environment. 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 it is shown in Figure 1, so that wrist movements are locked (to make sure that each subject just rotates their hand about their elbow). The subject grasps the end-effector of a haptic device (Sensable PHANToM^{TM} Omni device [12]). Once each subject is seated comfortably, their right arm and fingers are shielded from their own view with an opaque piece of black plastic. The focus is on the force thresholds for a user rotating the forearm about the elbow joint for the selected force directions and the increment/decrement of forces.

Attention is directed to the monitor containing a graphical display. As shown in Figure 2, the display shows a 2D virtual environment that is used to derive the JND for human force sensing. The 2D virtual environment contains a red 2D ball and two green rectangles. The center-to-center distance between the targets is 10.2 cm, and the width of the target is 1.3 cm. The 2D ball moves when the subject moves the haptic device. During each trial, subjects are asked to strike 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. Subjects are asked to score as many as hits they can.

On the other hand, subjects are also asked to accurately carry out the task. In other words, they must emphasize accuracy rather than speed. Unlike Fitt's task, subjects are required to maintain their hand's velocity within a specified range. The colour of the ball in the display is determined based on the subject's velocity and a 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 can control their velocity by observing the ball's colour. The mean value of the subject's velocity is always checked. The mean value is used because the subject has to stop at the end of the bar and move towards the other side of the bar. 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 may inadvertently apply extra force to see the red colour. This would distract the subject and affect the process of measuring the force thresholds. 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.

C. Stimuli

The force stimuli were presented by PHANToM^{TM} haptic device. The experimenter is able to change the parameters of the experiment through a computer. The experimenter can apply haptic effects to the subjects. Two forces vectors were used. As shown in Figure 3, the first one is called *opposed force*, a 150 mN base force that is opposed to the direction of the subject's hand movement is continuously applied to the subject's hand during each trial. The other one is called the *aid force*, a 150 mN base force is continuously applied to the subject's hand in the same direction as the subject's hand movement during each trial.

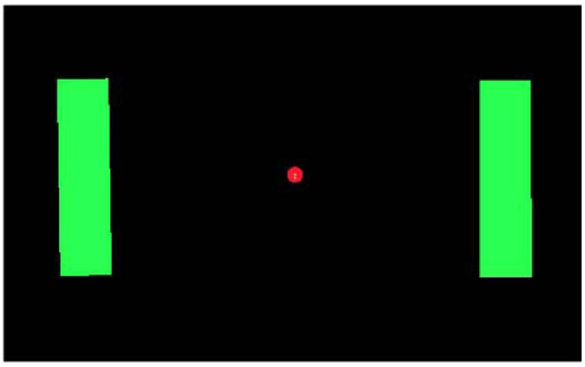

Fig. 2. The experimental setup: the 2D virtual environment

The velocity target is also set by the experimenter to 0.16-0.20 m/s. Before applying the force, the experimenter must ensure that each subject maintains their velocity within a desired (reference) range.

D. Design

The effects of force direction and the increment/decrement of the forces are studied through two experiments. This procedure is repeated two times for two different force directions. Therefore, each subject is required to participate in two experiments plus a one-hour training session. A range of velocity is selected based on the ability of a potential subject to carry out the task within the range of velocity. The range of velocity is chosen through experimental trial runs that were done before starting the main experiments. A *Repeated Measures* completely randomized two-factor design is employed in the experiments. The result is analyzed using the Repeated-Measures Analysis of Variance (RMANOVA). Each subject must carry out the two experiments in our repeated-measures experiment design. The experiments are randomly assigned to the subjects.

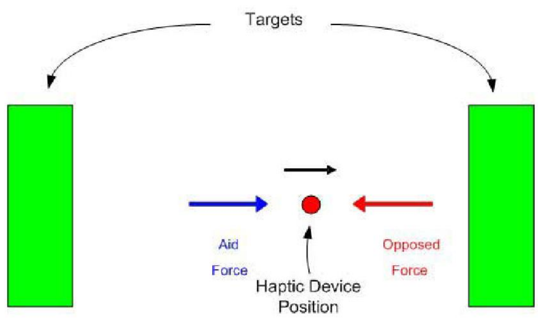

Fig. 3. The experimental setup: the 2D virtual environment

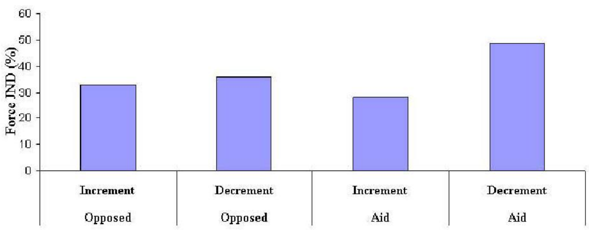

Fig. 4. Force direction and force increment/decrement

TABLE I. The average of Force JNDs based on force Direction and Increment/Decrement factors

Force Direction	Force Inc./Dec.	Mean	Standard Deviation
Opposed	Increment	32.93%	13.35%
Opposed	Decrement	36.05%	18.25%
Aid	Increment	27.98%	10.57%
Aid	Decrement	48.72%	12.78%

E. Procedure

The IS method from Section B, is employed to measure the JND in the force increment (upper limen) and in the force decrement (lower limen). In the middle of each trial, when the subject's hand velocity is within the desirable velocity range, the experimenter randomly increments/decrements the continuous applied base force based on the IS method. In IS method, the experimenter starts by presenting a sequence of forces (the base force plus the increment/decrement) which progressively increases or decreases in value (steps of 10 mN). Each experiment is done in 40 trials, 20 trials for each of two limens (upper and lower). Each trial contains two 15 seconds intervals (before and after increment/decrement of the base force).

V. RESULTS AND DISCUSSION

The average of JND values for all 6 subjects are shown in Table I for all levels of two factors. Based on the JND values, for example, if the force feedback on the user's hand is applied in the same direction as the user's movement, the user's hand velocity is within 0.16-0.2 m/s, and the force is decreased by less than 48%, then the user does not notice any changes.

A two-way RMANOVA is conducted to study the effects of the two force directions (opposed and aid) and the increment/decrement of the forces on the JNDs. In this paper, the analysis for all experiments is done at significance level of 0.05 [13].

The results of the two-way RMANOVA on the force direction and the force increment/decrement factor, F = 10.73 and p-value = 0.022, show that there is an interaction between the two factors (the force direction and the force increment/decrement). Thus, the effect of force direction on JND of the human haptic system is dependent on the increment or decrement of force.

We cannot look at the main effects of the force direction and the increment/decrement because of the interaction. However, it is possible to look at the simple effects of the force direction and the force increment/decrement. Therefore, four one-way RMANOVA are conducted to study the simple effects between each level of the force direction and the force increment/decrement. The RMANOVA on the increment or decrement of aid force, F = 38.9 and p-value = 0.0016, show that there is definitely a difference in the upper and lower limens of JND when the force is applied to the user's hand in the same direction of user's hand . Thus, the upper and lower limens of JND of the human haptic system are absolutely asymmetric in the application of aid forces.

However, the results for the increment or decrement of opposed force, F = 0.81 and p-value = 0.4092, strongly show that there is definitely no difference in the upper and lower limens of JND in the application of opposed force. As a result, the upper and lower limens of JND of the human haptic system are somewhat symmetric in the application of opposed force. As shown in Table I and Figure 4, the difference of force JNDs for opposed direction is very small. For example, if the force feedback on the user's hand is applied in the opposed direction of the user's movement, then the user is equally sensitive to increment or decrement of the applied force.

The one-way RMANOVA results for the force direction of the force increment, F = 2.28 and p-value = 0.1915, show that there is no difference between the opposed and aid forces in the case of force increments, meaning that the upper limen of the force threshold of the human haptic system is not affected by changes in the force direction.

The one-way RMANOVA results for the force direction of the force decrement, F = 5.7 and p-value = 0.0626, also show the same trend for the lower limen of the force threshold.

VI. CONCLUSIONS

As an application of the human factors data in this study, for example, an interface in [7] could be designed with the aid of a friction-reducing controller such that the friction is less than the 33% of applied force feedback in case of a small background force (e.g. 150 mN) when the velocity of user's hand is 0.04 m/s. Thus, any attempt to investigate the effect of forces and limens on the JNDs of force sensing in a quantitative manner is a significant contribution to the understanding of the human sensory-motor capabilities.

As mentioned in Section V, there is an interaction between the force direction and the force increment/decrement. Thus, one can not simply look at the changes in the force JND without looking at the force direction. Particularly, this is more critical in the applications when motion is involved.

It appears that the JNDs of human haptic perception depend on the force direction and the force increment/decrement, and these two variables must be incorporated in an efficient haptic design technique when the user's hand is in motion.

As discussed in Section V, there is a borderline significant simple effect of the force direction. Future work will investigate the resulting JNDs of this study with more subjects to see if there is any changes in the RMANOVA results of the force direction for the upper and lower limens.

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