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Perception of Haptic Force Magnitude during Hand Movements

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Abstract— **Haptic interfaces are used increasingly in medical systems and related applications, but relatively little is known on the effectiveness of these interfaces. This paper reports a study on the perception of haptic force magnitude during hand movements. Discrimination thresholds were determined for a reference force of 1.5N in five different directions ($0°$, $45°$, $90°$, $135°$, and $180°$) with respect to the movement direction. We found that force discrimination thresholds detected were significantly higher during hand movement than those reported previously without hand movement, indicating that the perception of force magnitude is impaired by hand movement. The results also show there is no significant difference between the discrimination thresholds found for fast (28mm/s) and slow (14mm/s) hand movements. Finally, we found that the perception of force magnitude is impaired at a force direction of $45°$ with respect to the hand movement, indicating the existence of an oblique effect.**

I. INTRODUCTION

Haptic interfaces have been widely used in applications such as surgical simulations and tele-operations [16], [1]. Recent studies have shown that haptic interfaces can also be helpful for human motor skill learning [10], [4]. As a consequence, various haptic motor skill training systems have been developed [6], [13].

It is well known that the more effort learners put in their training, the better their training outcome will be. Hence we need to optimize existing motor skill trainers so as to maximize the training outcomes. In our system for the collaborative training of cataract surgery (HAVE project [6]), we propose to dynamically modify the guiding force to facilitate learning. The idea is to provide maximum guidance at the beginning of the training and decrease the strength of the guiding force as the learner's skill is increasing. The learner is expected to take over movement control as the guiding force is reduced. In the case where the learner needs more assistance, the guiding force can also be increased. For such a system, it is important to know what force magnitudes are detectable.

The minimum change in force magnitude that is detectable is called discrimination threshold of force magnitude. Weber [15] observed that most thresholds are proportional to stimulus intensity and thus can be expressed as:

$$\frac{\Delta S}{S} = C,$$

where S represents the stimulus intensity, ΔS is the difference threshold or just noticeable difference (JND), and C is a constant, called the Weber fraction.

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There are a number of papers that investigated human perception of force magnitude. Findings are reported mainly in the form of difference thresholds. Allin et al. [2] assessed the sensitivity to haptic force magnitude applied to the index finger. The force was applied tangentially to the index finger's semicircular trajectory, and participants were required to press against the force to maintain their index fingers in a steady position. The study revealed a JND of approximately 10%.

Lee et al. [8] asked the participants to discriminate two haptic icons with different alignments using two different finger motions. The icons were lying on a horizontal plane at a distance of 4mm, and participants were asked to explore them using one of two different finger motions, flexion/extension or abduction/adduction. Force perception was not affected by the spatial arrangement of the haptic icons. Finger motion, however, affected force perception: The abduction/addition motion lead to a lower force discrimination threshold of 14.5mN as compared to one of 23.9mN for the flexion/extension motion.

Discrimination of force magnitudes also depends on the relative directions of the forces. Pongrac et al. [11] asked participants to discriminate pairs of forces applied to the stylus of a PHANToM device. In the reference stimulus a force was applied in a fixed direction (the reference direction), and in the comparison stimuli, a perturbation force was added to the reference force, in directions ($0°$, $45°$, $90°$, $135°$, or $180°$) relative to the reference force. Participants were required to keep the stylus steady to sense the forces. The force discrimination threshold depended on the direction of the perturbation vector: For directions $0°$ or $180°$, the JND was approximately 10%, and it was in the range of 20 - 30% for the other directions.

The reported thresholds or JND's were mainly obtained without hand or finger motions. In real world applications, however, hand motions are usually necessary for exploring a virtual environment or for performing certain tasks (e.g. in motor skill learning). It is thus important to know if and how hand motion affects the discrimination of force magnitude. To the best of our knowledge, no such study has been conducted so far. It is plausible to expect that force discrimination is more accurate when the hand is held steady, as in [2] and [11], than when it is required to be moved. This could be due to a number of factors, including the complexity of resulting force directions, as found in [11], or due to the fact that participants have to divide their attention between attending to the execution of a particular hand movement and attending to the discrimination of force magnitudes. We thus expected that the discrimination thresholds of force

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magnitude would be lower when hand movement is not required than when hand movement is required. In our study, we asked the participants to discriminate different force magnitudes with their hands involved in a left-to-right motion.

When hand motion is involved, it is also important to determine if and how hand movement speed affects haptic force perception. Lederman et al. [7], for example, found that perception of surface roughness was impaired by increasing the speed of relative motions. Wu et al. [17] found that performance in a force control task also decreased as the velocity of hand motion increased. In our study, we thus tested two different hand movement speeds, slow (14mm/s) and fast (28mm/s), to investigate the velocity effect in the perception of force magnitude.

Most of the existing haptic motor skill training systems either actively lead the learner's hand through an ideal trajectory or passively constrain the learner's hand movements within the ideal trajectory. In either case, the guiding force changes its direction continuously. Hence we were also interested in how human perception of force magnitude changes with the changes in force direction, and we tested five different force directions, $0°, 45°, 90°, 135°$, and $180°$ relative to the hand movement direction. These directions are the same as those tested in [5], [12]. For each direction, we obtained a mean force discrimination threshold to investigate a direction effect in the perception of force magnitude.

The rest of this paper is organized as follows. The experimental design and procedure are described in Section II, the results are reported in Section III. Then, the findings are discussed in Section IV. Finally, concluding remarks are given in Section V.

II. METHODS

A. Participants

Twenty five participants took part in this study. The group consisted of 3 women and 22 men between the ages of 20 and 30. All of the participants reported a normal sense of touch and vision. Two of the participants were left-handed, and the rest were all right-handed. The experiment took about 45 minutes, and the participants received $10 dollars for participation. The participants were informed about the purpose of the experiment, procedure, benefits, possible risks, and their rights. Every participant signed a consent form prior to performing the experiment.

B. Apparatus

The participants held the stylus of a PHANToM Omni haptic device from SensAble Tech. [14] as if they were holding a pen. The PHANToM was placed 38cm horizontally away from participants' shoulder. Participants had to insert their dominant arm into two velcro bands on an armrest, which was placed between participants' shoulders and the PHANToM device, so that their arm movements were restrained to minimize additional kinesthetic cues. The armrest was 5cm high, 38cm long and 21cm wide. The height of the armrest was sufficient to raise participants' wrists to a comfortable height for manipulating the stylus. A computer keyboard was placed next to the armrest for participants to enter responses with the non-dominant hand. Visual feedback was displayed on a 17-inch LCD monitor placed 38 cm in front of the participants. (Figure 1)

Fig. 1. Experimental setup for the study on the perception of force magnitude

III. STIMULI

Participants were required to move their hand at constant velocity from a starting point on the left to an end point on the right. During the hand movement, a force was applied to the stylus away from the movement direction, and participants had to detect magnitude differences in these forces. In the following, we first describe the forces that were applied, and then we describe the visual feedback that was given to control the hand movement.

Assuming the hand movement was along the x-axis, the force direction was either $0°$, $45°$, $90°$, $135°$, and $180°$ away from the x-$axis$, and on the cone defined by the x-$axis$ and the direction angle. The force could be in any direction, i.e. the phase angle of the force was chosen randomly in every trial (see Figure 2). For reference trials, the magnitude S of the force was $1.5N$, and for test trials, the force magnitude was $S \pm \Delta S$, where ΔS is a positive number representing the difference between the reference and test force. The value of ΔS was determined adaptively, as described below. The test force could thus be greater or smaller than the reference force.

The force was ramped up from 0 to the target value (either reference magnitude or test magnitude) within 1s of the trial start and ramped down to 0 within 0.5s of the end of the trial (see Figure 3).

A. Visual Feedback on Hand Movement

The task involved moving the stylus horizontally from a start position to an end position to form a left-to-right motion. The start and end position were graphically displayed by yellow 3D spheres of 1mm diameter and a distance of 42mm. The stylus position in the 3D space was represented by

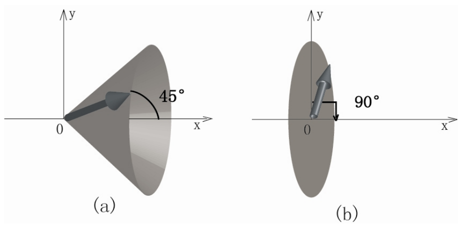

Fig. 2. The force vector could point in any direction, as long as the angle between which and the x-axis was equal to one of the force directions (0°, 45°, 90°, 135°, and 180°). For instance, if the force direction was 45° then the force could lie anywhere on the cone in (a) and if the force direction was 90° then the force could lie anywhere on the disc in (b).

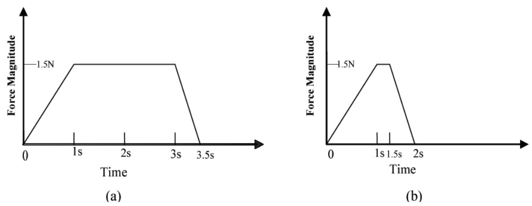

Fig. 3. Illustration of the temporal force magnitude curves for slow motion (a) and fast motion (b).

a blue spherical cursor (the dark sphere in Figure 4b). To prevent participants from moving off the straight trajectory, we put a virtual cylinder between the start position and the end position. The cylinder was 23mm high. It was made transparent so that the participants could see the cursor moving in it. The participants were instructed to move the cursor from the cylinder's left end to its right end without toughing the cylinder. Depth information is lost on a display, but it was particularly important to our participants because they used it to avoid touching the front and backside of the cylinder when adjusting the cursor's position. We thus also rendered a side view representation of the cylinder (the circle in Figure 4a) and the cursor.

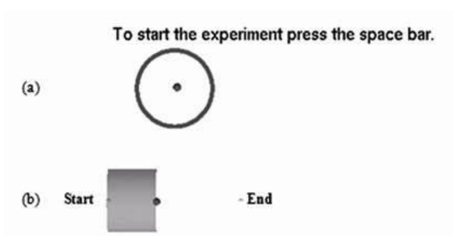

Fig. 4. The screenshot of the visual feedback. (a) The side view of the virtual cylinder and the main cursor. (b) The normal view, in which, the gray area between the start position and the main cursor is the progress bar

Before moving the main cursor, participants were asked to adjust the position of the cursors to place them in the middle of the cylinder. After the start, the participants had to check both, the normal view and the side view, to make sure the cursors were moving inside the cylinder and did not touch the cylinder.

To facilitate the velocity control, we used a progress bar (see Figure 5). The red speed bar had the same height as the cylinder. It started from the start position and progressed right in the desired speed until it crossed the end position. Participants were asked to follow the speed bar while moving the main cursor in order to meet the speed requirement. We used another progress bar to show the horizontal position of the main cursor (see Figure 4b). This progress bar was similar to the speed bar except that its right end followed main cursor's horizontal position. The blue progress bar was made semi-transparent so that through which the participants could always see the speed bar. To move at a desired speed, the participants needed to place and maintain the right end of the progress bar as close as possible to the right end of the speed bar.

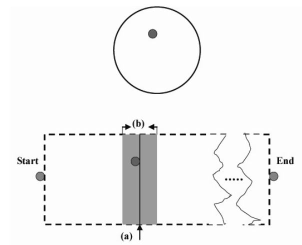

Fig. 5. This sketch shows (a) the right end of the speed bar and (b) the tolerance region of the speed bar. The dashed lines indicate the virtual tube.

Given that it is difficult to move at a precise speed, we created a tolerance region for the speed bar. It was 1mm wide on each side of the right end of the speed bar. It worked in a way that as long as the right end of the progress bar was maintained inside the tolerance region we considered it following the desired speed. In such case, the cursors were painted yellow to indicate a "following" status. At any time the participants did not follow the speed bar, the cursors turned to red to indicate a "not following" status. In addition, we created another tolerance region for the start position (Figure 6). It was 2mm wide to the right of the start position. The participants could place the main cursor anywhere within the tolerance region to start a trial. As long as the main cursor was placed in the tolerance region of the start position, the progress bar and the cursors were painted by yellow to indicate a "good-to-go" status.

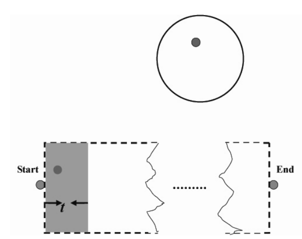

Fig. 6. The gray area t indicates the tolerance region of the start position. The dashed lines indicate the virtual tube.

B. Procedure

The participants performed warm-up trials before the actual experiment to ensure that they were able to master the moving task so that they could attend to the task of discriminating force magnitudes. The participants were asked to practice as much as they wanted until they could master the task. The warm-up sessions took between 5 and 20 minutes.

The task required the participants to discriminate force magnitudes while moving the main cursor from the cylinder's left end to the right end at a desired speed, without touching the cylinder. Before starting a trial, the participant placed the main cursor in the tolerance region of the start position, where he or she could see the progress bar and the cursors turned to yellow to indicate a "good-to-go" status. The participant was also asked to adjust the cursors' positions by placing them in the middle of the cylinder. This ensured a good starting position to avoid touching the tube wall while moving. After a trial was started, the participant moved the progress bar to follow the speed bar by placing the right end of the progress bar in the tolerance region of the speed bar.

An experiment consisted of a number of blocks, and each block consisted of three trials, two with the reference force (S) and one with the test force ($S \pm \Delta S$). In each trial the current stimulus numbers (1, 2, or 3) and the desired hand movement speed were clearly displayed on the computer monitor. The three trials within a block were randomly ordered, and participants had to indicate which of the three trials had a different force magnitude by entering 1, 2, or 3 on the keyboard. Responses were recorded and used to determine the value of ΔS in the next block. For each trial, the participant's hand movement was analyzed for validity. If s/he followed the speed bar at least 90% of the time then his/her their hand movement was considered as a good trial, and the next trial was presented. If not, the whole block was restarted.

The discrimination threshold of haptic force magnitude was found using a one-up-two-down adaptive staircase method [9], which tracks a level of 70.7% correct responses. The force magnitude S was set to $1.5N$, the step size ΔS was initially set to $0.2N$, and it was increased by $0.2N$ after each incorrect response and decreased by $0.2N$ after 2 consecutive correct responses. After 5 reversals, ΔS was set to $0.02N$. A staircase run was terminated after 10 reversals with ΔS = 0.02N. In other words, there were 15 reversals in each staircase run. The experiment finished after two staircase runs were completed.

The participants were not given feedback about the correctness of their responses in either the warm-up blocks or the experimental blocks.

C. *Experimental Design*

Participants were divided into five groups. Each group tested one of the force directions at two levels of hand movement speed, slow (14mm/s) and fast (28mm/s). The force directions were randomly assigned to the groups, and the speed levels were fully counter-balanced

IV. RESULTS

One participant was not able to finish the experiment. So data from 24 participants were analyzed. The average from the last 10 reversals were calculated for each participant. Each participant's discrimination threshold was then calculated by averaging these means. The estimated discrimination threshold of haptic force magnitude for each force direction was computed by averaging the thresholds of the corresponding group (Table I). The estimated thresholds were analyzed using a two-way mixed analysis of variance (ANOVA) with force direction as a between-subjects factor and (hand-movement) speed as a within-subjects factor.

The ANOVA analysis concluded that there was a significant effect of force direction, $F(4, 38) = 6.91,\ p < 0.001,\ \eta^2 = 0.41$; means are shown in Table I. There was no effect of hand-movement speed, $F(1, 38) = 0.25,\ p > 0.05,\ \eta^2 = 0.004$; and no interaction between force direction and hand movement speed, $F(4, 38) = 0.43,\ p > 0.05,\ \eta^2 = 0.03$. Tukey-Kramer tests showed that the discrimination threshold found for $45°$ with fast motion was different from the discrimination thresholds found for 0° with both, fast and slow motion.

TABLE I
AVERAGE THRESHOLDS AND JND'S AS A FUNCTION OF HAND MOVEMENT SPEED AND FORCE DIRECTION.

	Force Direction					
Speed:	0°	45°	90°	135°	180°	Average
Fast	$0.49N$ 33%	$1.01N$ 67%	$0.84N$ 56%	$0.6N$ 40%	$0.51N$ 34%	$0.69N$ 46%
Slow	$0.44N$ 29%	$0.83N$ 55%	$0.8N$ 53%	$0.69N$ 46%	$0.52N$ 35%	$0.66N$ 44%
Average	$0.47N$ 31%	$0.92N$ 61%	$0.82N$ 54.5%	$0.65N$ 43%	$0.52N$ 34.5%	$0.68N$ 45%

V. DISCUSSION

The relatively high force discrimination thresholds found in this study indicate that the perception of force magnitude is impaired when the hand is moving, as opposed to conditions when the hand remains static (see [2] and [11]). The results also suggest that, in systems where haptic force magnitude needs to be changed frequently, the magnitude of haptic force change may even need to be higher than 67% of the original force in order to be well noticeable (see Table I). This implies that some of the low-end haptic devices in the current market may not be suitable for the tasks requiring dynamic force magnitude changes because they may not produce force magnitude sufficiently high of haptic interactions.

As mentioned in the first section, we hypothesized that the discrimination thresholds of force magnitude are lower when no hand movement is required than when hand movements are required. To confirm this hypothesis, we compared our findings with the threshold reported in the literature where no hand motion was involved. The discrimination thresholds reported in the literatures are approximately 10% [2], [11], they were found on the participants' steady index fingers or on a steady stylus. Our discrimination thresholds were found by measuring force magnitude changes when moving a stylus. The discrimination threshold reported in the literature were found only for 0° and 180°, so only the 0° thresholds (31%) and 180° thresholds (35%) were used to compare with our findings. Our findings show that when hand movement is involved the average JND is 33%, which is considerably higher than the reported 10%. Therefore, we suggest that human perception of force magnitude is impaired by hand motion.

A statistical analysis of the experimental data showed that the speed of hand movement did not affect the perception of force magnitude. Figure 7 shows that the threshold curves of were similar for fast motion versus and slow motion. However, we believe people normally explore virtual worlds within a range of hand movement speeds. The upper bound of the range refers to the speed limit that people normally do not exceed. Within that range, people appear to be able to precisely perceive the virtual world haptically without being affected by hand movement speed. However, if hand movement speed exceeds the upper speed boundary, haptic perception should be impaired. This may be attributed to the velocity effect or due to reduced duration of haptic stimulation. To the best of our knowledge, such speed limit has not been reported. We chose the speed levels based on our observation of the speeds with which people usually move their hands to perceive the virtual world. Thus the tested speed levels were falling into a range of practical importance. Therefore, we suggest that hand movement speed does not affect human perception of force magnitude when it falls into this range. The velocity effect may appear when hand movement speed approach or exceed the speed limit.

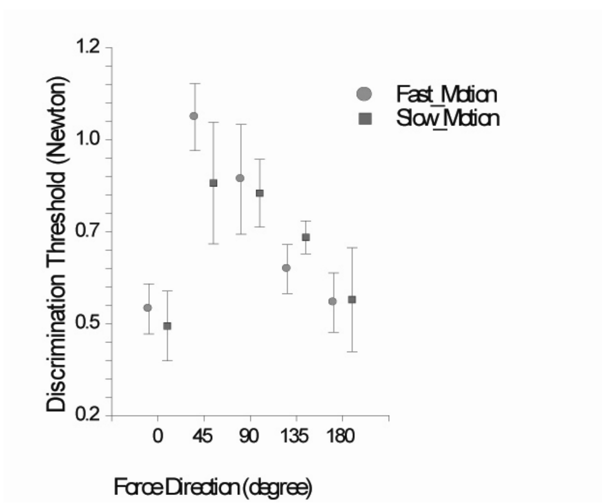

Fig. 7. Discrimination thresholds of force magnitude at two speed levels upon five force directions. Average and standard errors are shown.

Regarding the direction effect, the perception of force magnitude was found to be affected by force direction. More precisely, the discrimination threshold for 45° direction and fast movement (Average Threshold = $1.01N$, JND = 67%) was different from the one for 0° direction and fast movement (Mean Threshold = $0.49N$, JND = 33%) and for 0° direction and slow movement (Mean Threshold = $0.44N$, JND = 29%). Among all the groups, the group with 45° orientation and fast movement had the highest discrimination threshold and the one with 0° orientation and slow movement had the lowest discrimination threshold. This shows that humans perform very differently for these force directions. Pongrac et al. [11] found effects of force direction similar to those reported here. They also found 45° had the highest discrimination threshold. Based on these findings, we suggest that the 45° direction is a weak point for humans to perceive force magnitude. Our conclusions cannot go beyond this, as we did not find differences between 45° direction and the other directions (90°, 135°, and 180°). More work is required to find an adequate explanation for this phenomenon

There is some evidence showing human perception to be impaired in oblique directions (45° and 135°) [3]. This impairment is called oblique effect. Given that human perception of haptic force magnitude is impaired for the 45° direction, we believe that the oblique effect affect the perception of force magnitude. However, in contrast to the 45° direction, our study does not reveal impairment for the 135° direction. Since the present study only tested the left-to-right motion, we do not know whether the oblique effect exists only at 45°, or whether it depends on the direction of hand movement.

VI. Conclusion and Future Work

This paper reports an experimental study of human perception of haptic force magnitude. We measured the discrimination thresholds of haptic force magnitude and found that humans have a relatively poor sensitivity to force magnitude. The perception of force magnitude can be strongly impaired by hand motions. We also found that hand movement speed did not affect the perception of force magnitude. However, this result was only found with hand movement speeds in a practical range. Our studies of the direction effect suggest that the perception of force magnitude depends on force direction. In particular, people have poorer perception at 45° direction. This indicates the existence of oblique effect. Future work will focus on finding proper explanations of direction effect. Also, more studies are planned to confirm the oblique effect. As mentioned, there is no study conducted on the practical speed range. So experiments will be designed to confirm and identify the speed range.

VII. Acknowledgments

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