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Estimation of Vibration and Force Stimulus Thresholds for Haptic Guidance in MIS Training

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ESTIMACIÓN DE UMBRALES DE PERCEPCIÓN DE FUERZA Y VIBRACIÓN PARA GUIADO HÁPTICO EN ENTRENAMIENTO DE MIS

Abstract — This manuscript investigates the minimum perception thresholds for force and vibration stimuli in a simple movement pattern and using the same haptic device. The model was model derived from the well-known *Up-Down Transformed Response Rule* varying the force magnitude and the amplitude of vibration feedback. It was demonstrated that the vibration sensitivity was around fifteen times smaller than the force threshold. The results were compared with previous published studies for different tasks, experimental configurations and devices. We concluded that the type of task significantly affects human detection threshold for force and vibration feedback, and should be adapted for the design of a new haptic-based skill transfer system for minimally invasive surgery (MIS) using haptic guidance.

Keywords — Force Threshold, Haptic Perception, Steering Task, Vibration Threshold.

Resumen — El presente artículo muestra los resultados de una investigación para determinar los umbrales de mínima percepción ante estímulos de fuerzas y vibraciones aplicados durante la realización de un movimiento simple y utilizando el mismo dispositivo háptico. El modelo utilizado se derivó del bien conocido método de *Up-Down Transformed Response Rule* donde la retroalimentación fue variada en términos de la magnitud de la fuerza y de la amplitud de la vibración. Se demostró que la percepción de vibración fue alrededor de quince veces más pequeña que el umbral de fuerzas y se compararon los resultados con trabajos previos para diferentes tareas, configuraciones experimentales y distintos dispositivos. Se concluyó que el tipo de tarea afecta significativamente el umbral de detección humano tanto para retroalimentaciones de fuerzas como de vibraciones. Además es fundamental considerar estos valores en el diseño de nuevos sistemas de guiado hápticos para el entrenamiento de habilidades requeridas en Cirugías Mínimamente Invasivas (MIS por sus siglas en Ingles).

Palabras Clave — Guiado Háptico, Percepción Háptica, Umbral de Fuerza, Umbral de Vibración.

I. INTRODUCTION

Haptic guidance has been used in medical applications, especially in steering tasks for surgical training. Currently, several surgical procedures such as gall bladder removal, eye surgery, neurosurgery and tumor ablation, include minimally invasive surgery (MIS), with the aim to decrease the risk to the patients. However, MIS has significantly reduced the sense of touch compared to open surgical methods, making training of novices more complex [1]. In the case of eye surgery and laparoscopic interventions, surgical training has been mainly done with training boxes and virtual reality based systems, improving

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surgical knowledge transfer even though the simulation is not accurate enough. In the design of training devices, one of the most valuable tasks is the performance assessment of the trainee without subjectivity. For this reason, haptic guidance uses a model for transmitting tactile feedback according to the magnitude of the error with respect to a reference trajectory. This method can be used to evaluate the performance of novice surgeons during training, and it is deemed to be a good method for improving skill transfer [2, 3].

To date most research evaluating task performance in surgical simulation has focused on the comparison between visual and haptic feedback for different applications, and has demonstrated the importance of tactile feedback for interactions [4, 5]. Considering the difficulty of realistically simulating a surgery, it is indispensable to begin with simple tasks, where key factors can be controlled, and then move forward to more complex simulations.

Our main interest is to investigate how haptic guidance can be used in surgical training, especially for MIS. But first, it is important to investigate haptic sensitivity in such tasks in order to achieve realistic and optimal simulations. Earlier work with force-guidance has shown that haptic thresholds are dependent on the type of task, such as drawing a line, a circle or a square [6-8]. Dosher and Hannaford applied an adaptive method to determine the effect of amplitude, size, shape, and pulse-duration of a haptic icon for hand held devices [7]. King et al. analyzed the effect of force feedback with a single and a multi-finger interface [8]. Salisbury et al. measured haptic sensitivity of vibration in a static position for various commercial haptic devices [9]. To our knowledge, there is no study that evaluated force and vibration sensitivities in the execution of the same task and using the same device.

Haptic sensitivity thresholds depend on multiple factors, including the task and the measurement device. Thus, this work seeks to compare vibration and force threshold with a relatively simple and consistent movement in both circumstances, i.e. drawing a circle. The results of this study allow defining specifications of assisting steering tasks based on empirical values of force and vibration sensitivity.

In this work, it was determined the force and vibration sensitivity on the task of drawing a circle. Related work on tactile sensitivity is reviewed in Section 2. In Sections 3, the experiments with force and vibration feedback are described, followed by the results and discussion of each experiment in Section 4. Finally, Section 5 includes the conclusion of the present study.

II. RELATED WORK

a) Estimation of Force and Vibrotactile Perception

Several studies have been carried out on haptic sensitivity for both force and vibration perception. Unfortunately, these experiments have used different devices and have found substantially different thresholds for the same sense [9]. Thus, it is difficult to directly compare force and vibration thresholds. In this study, the same task and same device were used, making such comparison possible.

Dosher and Hannaford studied force thresholds using a fingertip haptic display (FHD) [7]. They reported results on the perceptual effects of varying the characteristics of an attractive force field located between two lines. They modified the lines width, force distribution and they also included active and passive exploration. The study also considered an adaptive threshold finding algorithm to determine the minimum amplitude for the haptic effect. They found that the difference between icon width and force threshold value was not statistically significant. In the experiment, a force pulse was applied to a non-moving finger, and results indicated that there was no statistically significant relation between pulse duration and threshold. Sinusoidal force distribution resulted in a detection threshold almost twice that of saw-tooth shaped icons. A limitation however, was that the study did not include the analysis of vibration feedback during the same task.

King, Donlin and Hannaford measured the haptic sensitivity for multi-finger single point interaction [8]. They used a multi-finger haptic display (MFHD) to interact with small icons with attractive forces located in different virtual planes. Participants had to identify the icon that provided force feedback. The results showed comparable force sensitivity thresholds between index finger, middle finger and little finger, but less sensitivity with the ring finger. Furthermore, results indicated that multi-finger feedback did not increase the sensitivity to small haptic stimulus compared to a single finger.

In a study on vibration sensitivity, Salisbury et al. found that the design of three commercial haptic devices (the Phantom Premium 1.0, the Phantom Omni, and the Falcon) may affect the vibration stimulus threshold [9]. Participants executed a passive exploration. Participants were also presented with three randomly ordered stimuli and had to identify the signal that vibrated at a frequency of 40 Hz or 160 Hz. Results indicated that the vibration threshold with the Phantom Premium seemed to be lower than those of the other two devices. The results also indicated that none of the tested haptic devices was capable of rendering perceptually undistorted, periodically regular vibrations.

In summary, for the aforementioned studies, none of them included tasks that measured vibration sensitivity in active movements and neither compared force sensitivity threshold to vibration sensitivity thresholds with the same task and same device.

III. MATERIALS AND METHODS

This work investigated the haptic stimulus thresholds levels that allow a comparison between vibration and force thresholds using the same device and the same motion trajectory. The minimum perception threshold was determined for participants whom were asked to draw a circle using a haptic device (PHANTOM Omni, Sensable Technologies). A reference trajectory was drawn and was used to determine the constraints and subsequent feedback during the experiments.

3.1 Experiment 1: Force Sensitivity Threshold

A. Apparatus

The PHANTHOM Omni is a haptic device with six degree-of-freedom positional sensing. It has a nominal position resolution of approximately 0,055 mm and a maximum force of 3,3 N. The test system was developed in Matlab version R2008a using Simulink. The haptic guidance was implemented using QuaRC, the Control Software Package from Quanser. Participants sat at a desk at a viewing distance of 45 cm from the circle and held the device interface with their dominant hand. They were asked to hold the stylus of the haptic device like a pen while they draw a circle (Fig. 1). Their movement was guided through an attractive force field.

Fig. 1. Experimental Setup showing the Phantom Omni device and a participant drawing a circle.

B. Guiding Forces

The guiding force was activated when the stylus end-effector deviated from the reference trajectory, and the end-effector was dragged back to the reference path. The magnitude of the guiding force was not proportional to the distance between the end-effector and the reference trajectory, as is the case in the most passive force guidance work. Instead, the attractive force field exerted a force according to the location of the end effector. The direction of the correction force was calculated by estimating an unit vector in the same direction as the minimum distance vector between the end-effector position and a point from the reference trajectory (Fig. 2). The goal was to guide the user's hand to the nearest point on the reference path. In regions of non-zero force, the force magnitude had a constant component and a damping term that stabilized the system to decrease unwanted vibrations. The total force was determined by Equation 1:

$$F_{Total} = F_{Stiffness} + F_{Damper} = \frac{K}{10} + D\frac{\partial x}{\partial t}, \quad (1)$$

where K and D describe the stiffness and damping constants and x is the end-effector position. The stiffness constant varied in each trial according to the up-down transformed response rule (UDTR) to estimate force sensitivity [10]. The end-effector position was measured using the joint and gimbal angles.

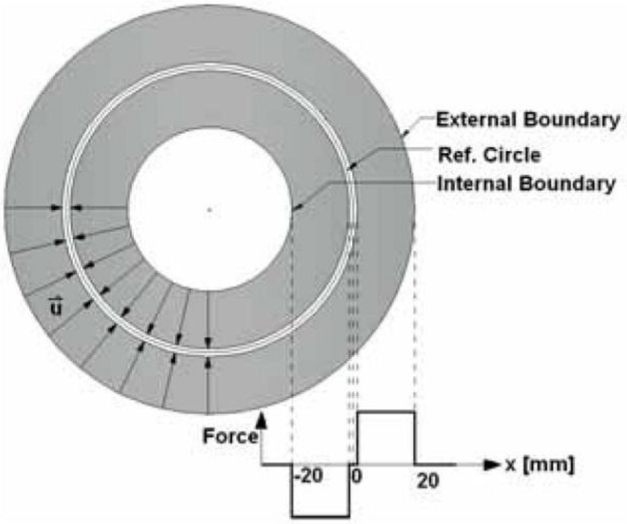

Fig. 2. Scheme of the reference circle and the direction of the force. The grey regions represent the locations where the force is constant and nonzero.

Damping force was added to the system to mitigate instability of the motor control, but the magnitude of this component was negligible compared to the stiffness force. The dashpot constant was defined as a function of the stiffness constant K. Accordingly, the total force applied to the system was defined by Equation 2:

$$F_{Total} = \begin{cases} 0 & if\ |\Delta x| \leq 1.5\ or\ |\Delta x| > 20mm \\ \frac{K}{10}\vec{u} + \frac{K}{10000}\frac{\partial x}{\partial t}\vec{u} & otherwise, \end{cases} \quad (2)$$

where $\vec{u}$ is an unit vector, normal to the trajectory of reference, and is always in the direction to the reference circle. A saturation force to avoid damage to the equipment was defined. In addition, the force was set to zero in the first 100 ms of each trial in order to avoid an initial pulse when the system was initialized.

C. Experimental Design

Two female and one male (age 22 - 23 years old) participated in the study. All were right-handed and had few months of experience interacting with haptic devices. To determine the initial stiffness force constant *K* and the step size, we first ran a pilot study to establish parameters that allowed us to determine the threshold in a reasonable number of trials. The participants were asked to draw twice a circle of 120 mm diameter based on a reference drawing by holding the pen perpendicular to the plane of the circle, to move it with a controlled speed, and to draw the circles always in the same direction. Participants wore headphones playing music to mask auditory cues from the haptic device. In one of the two attempts, participants received a constant attractive force stimulus that indicated that they were not located close to the reference circumference. A virtual "tunnel" was defined along the reference trajectory, in order to avoid instability due to the changing force direction. After each trial the participants were asked to determine which repetition included force feedback to facilitate the drawing. This process was repeated 40 times per participant. The UDTR method was used using a stiffness constant *K* that varied per trial considering a step of 0,5. We used a two-interval, force-choice, one-up and two-down adaptive thresholding method which yields a detection threshold of 71% correct. The definition of the step size and the initial value for was determined during the pilot study. Participants were asked to control the speed so as to avoid unexpected increments in the force feedback due to the damping component.

The experiment was organized into 3 blocks, one per participant. Each block consisted on 40 trials, and each trial included the drawing of 2 circles. The experiment took approximately 40 minutes per participant. Using the results we did an ANOVA to evaluate possible significant differences between participants. Once it was probed the existence of significant differences, we implemented a pair-wise comparison of the means using least significance differences (LSD).

3.2 Experiment 2: Vibration Sensitivity Threshold

The vibration threshold in a simple movement pattern was studied. The task involved steering a cursor around a circle; but when the participants moved the stylus tip away from the reference path, they perceived a vibration instead. The threshold amplitude of the vibration feedback was investigated. Participants, apparatus, procedure, and experimental design were identical to those described in section 3.1 (Experiment 1), with the exception that the vibration amplitude was manipulated rather than the magnitude of the guiding force.

A. Vibration Guidance

In the vibro-tactile feedback we used a reference path and measured the minimum distance between the target and the tip of the stylus. The definition of the vibration feedback is given by Equation 3:

$$Vib = Amp(sin(2\pi ft)) \tag{3}$$

where, *Amp*, *f*, and *t* describe the amplitude, frequency of the signal, and the sample time, respectively. Sample time of 1 *ms* was used, and six samples per period of time were included, resulting in frequency of 166 *Hz*. The vibration amplitude was increased or decreased according to the UDTR method. The amplitude of the vibration was constant in each trial and was determined by Equation 4:

$$Vib = \begin{cases} 0 & if\ |\Delta x| \leq 1.5\ or\ |\Delta x| > 20mm \\ Amp(\sin(2\pi ft)) & otherwise \end{cases} \tag{4}$$

It is important to note that vibration was not generated when the tip of the stylus was not touching the plane of the circle. We also defined a saturation value to prevent possible damages to the device and the vibration was set to zero in the first 10 *ms* of each trial, when the device was started.

IV. RESULTS AND DISCUSSION

4.1 Experiment 1: Force Sensitivity Threshold

For each trial, the value of *K* and the user's choice were recorded. Every participant completed 40 trials and the force sensitivity was computed by averaging the force in the last 15 trials. The mean threshold and standard-deviation over the last 15 trials for the three participants considered in this experiment were calculated (Fig 3.). An ANOVA of the results indicated significant differences between participants, $F(2,45) = 134{,}2$, $p < 0.001$ rejecting the null hypothesis. A pair-wise comparison of the means using LSD indicated that the absolute difference between participant 1 and 2, which corresponded to $2{,}77 \times 10^{-17} N$, was not statistically significant, whereas the difference between participant 3 and the other two was significant with an absolute difference of 0,243 *N*.

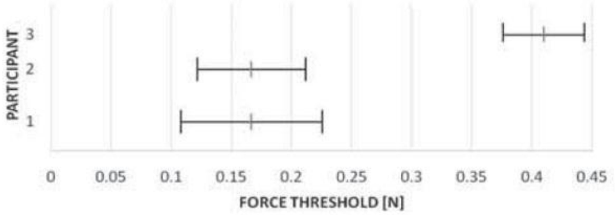

Fig. 3. Force threshold distribution for the three participants in experiment 1. Mean ± one standard deviation is indicated.

The average thresholds in our experiment corresponded to the minimum detectable force between two repetitions of drawing a circle. A previous study used a sample size of six people, and obtained that the mean and standard deviation for single-finger force threshold were 27,7 *mN* and 5,5 *mN* [7]. Our experiment used three subjects and an estimated mean force detection threshold of 247,8 *mN* with a standard deviation of 45,85 *mN*. A two-sample t-test showed that these differences were significant, ($t_2 = 8,3$, $p < 0,05$), between our study and the one done in [7]. The differences between the experiments can be attributed to differences between the devices, the trajectories (two lines vs. one circle), the force distribution (saw-tooth vs. rectangular), and the size of the haptic icons (two lines placed 2 *mm* apart vs. a circle of 120 *mm* diameter). We also compared our results with the ones found by King et al. [8]. Their results for multiple finger force thresholds showed an average of 28.9 *mN* and standard deviation of 9.9 *mN*. The difference between their and our results is also significant, ($t_2 = 8,2$, $p < 0,05$). The reasons for such differences were the same in Dosher et al. [7] work. Furthermore, in our experiment, participants were provided with haptic feedback while drawing one circle and no haptic feedback while drawing the other circle. In contrast, the participants in the aforementioned studies were able to go back and forth, within the same trial, between the icon with haptic feedback and the one without [7, 8]. For this reason, they were able to compare the two feedbacks repeatedly. Finally, our reported threshold is higher than that in Dosher et al.'s and King's since the friction of the Phantom Omni is much higher than the other's devices. This may explain the differences in the threshold values obtained in our study and the others.

4.2 Experiment 2: Vibration Sensitivity Threshold

The value of the amplitude of the wave and the user's choice per trial was stored. The mean threshold and standard-deviation of the wave amplitude for the three participants over the last 15 trials were calculated (Fig 4.). An ANOVA of the results indicated significant differences between participants, $F(2,45) = 34,55$, $p < 0,001$. Using Fisher LSD method we found significant differences among all the participants in the estimation of the vibration stimulus thresholds, with absolute differences of 4,133 *mN*, 2,267 *mN* and 6,4 *mN* between participants 1-2, 1-3, and, 2-3, respectively.

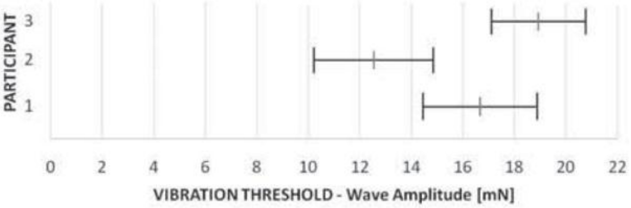

Fig. 4. Vibration threshold distribution for the three participants in experiment 2. Mean ± one standard deviation is indicated.

It was observed significant differences among all participants in the estimation of the vibration stimulus threshold. Participants indicated that it was easier to find the correct answer in the vibration threshold experiment than the experiments with force feedback. Correspondingly, convergence was faster than in force threshold estimation. We attribute this to perceptual differences between tactile and kinesthetic senses.

The average vibration threshold corresponded to the minimum detectable vibration between repetitions. We compared our experimental results with results obtained by Salisbury et al. [9] who also used the Phantom Omni haptic device. They obtained a higher vibration threshold ($M = 58,2$ *mN*, $SD = 9,8$ *mN*) at a frequency of 160 *Hz*. In contrast, our average threshold was 16 *mN* ($SD = 2,1$ *mN*) at a similar frequency, a difference that is significant, ($t_{4.6} = 9,33$, $p < 0,05$). However, it is important to note that Salisbury et al. studied static detection thresholds under no motion whereas this research studied it under movement. It is known that under movement the thresholds are higher [6]. Furthermore, the current work requires users to hold the stylus vertically, perpendicular to the direction of applied vibration motion, compared to horizontally along the axis of vibration which was the case in (Salisbury 2009). This means that the reported force is not the force being applied across the hand, since the hand is at a fulcrum relative to the point of applied force (the stylus axis). This also reduces the effective mass of the system, since the stylus plus hand do not have to be accelerated.

4.3. Limitations

This study considered force and vibration thresholds for the same task and using the same haptic device. However, the validation of the results was limited to comparison with previous studies [6-9], that used different devices and participants. Hence, it was not possible to warrant that the exact same tasks were performed.

V. CONCLUSION

In this paper, we reported experiments aimed at studying the difference for the minimum perception threshold for vibration and force stimuli, in a simple movement pattern, i.e. the task of drawing a circle, and using a Phantom Omni haptic device.

To our knowledge, this is the first time that force and vibration sensitivity were evaluated during the execution of the same task and using the same device. The results demonstrate that the type of task significantly affects the detection threshold for force and vibration feedback. In both experiments, we obtained results that were different from those reported previously, which is possible explained by the use of a different haptic device, which according to Salisbury et al. [9] affects the perception thresholds. Our force threshold was 10 times larger than the one reported previously [7, 8] using a FHD and a MFHD haptic display, in which different types of active exploration were analyzed. Despite to the fact that in our study the adaptation in the vibration threshold experiment was more noticeable in the first experiment, it was observed that larger relative differences in the average vibration threshold among participants than in the force threshold estimation.

Based on our results, we are developing a more complex system to teach MIS with haptic guidance. We are planning to install operating room (OR) ready haptic system capable of applying and measuring the position of operating tools for eye surgery, neurosurgery and laparoscopy. Our goal is to find a model for the task where the force, vibration and visual guidance is provided in an active manner to transfer MIS procedures between trainer and trainee surgeons.

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