The Investigation of Laparoscopic Instrument Movement Control

Hung-Jen Chen, and Chiuhsiang Joe Lin

Abstract—Laparoscopic surgery avoids large incisions for intrabdominal operations as required in conventional open surgery. Whereas the patient benefits from laparoscopic techniques, the surgeon encounters new difficulties that were not present during open surgery procedures. However, limited literature has investigated in the essential movement characteristics such as magnification, amplitude, and angle.

For this reason, the present study aims to investigate the essential movement characteristics of instrument manipulation via Fitts' task. Ten right-handed subjects made discrete Fitts' pointing tasks using a laparoscopic trainer. The factors were amplitude, magnification and angle. Movement time and throughput were recorded as dependent variables.

The experimental results showed that there were significant differences between the three factors in movement time and in throughput.

These findings pointed to a design direction for the laparoscopic surgery training program in the training procedure.

Keywords: amplitude, angle, Fitts' law, laparoscopic surgery, magnification

I. Introduction

LAPAROSCOPIC surgery, or minimally invasive surgery (MIS), has entered widespread use in recent years. This new surgical approach avoiding large incisions for intrabdominal operations as required in conventional open surgery. In laparoscopic surgery, a surgeon performs a surgical operation by using instruments through three or more trocars (ports) into the abdominal cavity (each hole is about 10 mm in diameter) which permit the introduction of a camera-monitored telescope and two or more fine instruments to perform the operation in a similar manner as, formal, in open surgery. Due to the small incision, the patient experience less trauma during surgery and more rapid recovery than with open surgery, and the medical cost is reduced [1-4]. This new approach requires, in comparison to open surgery, an additional spectrum of devices and technical support (lights sources, camera, control unit, insulator, video screens, etc). Thus, laparoscopic surgery is highly advantageous for the patient. However, it is necessary for the surgeon performing such surgery to possess high surgical skill.

Whereas the patient benefits from laparoscopic techniques, the surgeon encounters new difficulties that were not present during open surgery procedures. These difficulties include: limited degrees of freedom, two-dimensional monitoring (2-D) of the three-dimensional (3-D) surgical field, and awkward instruments with inferior force transmission properties relative to their open surgery equivalents [5].

The intrabdominal image displayed on a video monitor is a 2-D image and, therefore, lacks accurate depth perception. To overcome this lack of depth perception the operating surgeon uses a variety of monocular or 2-D cues, namely, light and shade, relative size of objects, object interposition, texture gradient, aerial perspective, and, most important, motion parallax [6]. These cues compensate somewhat for the lack of depth perception of 2-D vision, but do not make up completely for the accuracy of the 3-D imaging. The surgeon often has to find the position of instruments by touching the organ or tissue to be cut or manipulated and so determine their position before using them. As a result, surgical tasks that take seconds during open surgery can take minutes during laparoscopic surgery. Although the repeated training and practice can improve surgeons' skill to shorten operation time and prevent errors [7], and therefore those training programs are not designed based on the essential characteristics of motor control model under the situation lacking depth perception.

In industrial engineering field, engineers have always been concerned with the prediction of human motion time. Many successful prediction methodologies have been in use in industrial for many years. Because of the need for a publically available methodology for prediction of micro-miniature assembly times, the time prediction system was developed by Hancock, Langolf, & Clark [8]. The system called MTM-M is unique in industrial engineering because it uses the Fitts' Index of Difficulty (ID) [9, 10] as a predictor of motion time. Subsequently, Langolf & Hancock [11] investigated the ultimate quality of the ID as a predictor of microscopic motion time, and also investigated the effect of microscope power under conditions more carefully controlled than possible in the MTM-M industrial studies. This laboratory study showed that proper transformations of other task variables: part size, part position uncertainty, and difficulty of subsequent motions can be used to quantitatively predict nearly all of the remaining motion time variance. However, these studies mainly focused on the characteristics of human motion patterns performed in conjunction with the stereo microscope, those under monocular situation as a research field has not yet been much addressed.

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As described above, understanding the essential characteristics of motor control model is fundamentally important for laparoscopic surgery development and designing training programs. For this reason, the major propose of this study is to address the essential characteristics of laparoscopic instrument movement control under lacking depth perception laparoscopic surgery situation.

II. Methods

The present study aims to investigate the essential characteristics motor control model of instrument manipulation while performing laparoscopic surgery via Fitts' task [9, 10]. In order to achieve the objectives of this study, the Fitts' pointing task was conducted and described in detail as following sections.

A. Participants

Ten right-handed Industrial and Systems Engineering graduate students of Chung Yuan Christian University participated in this experiment, aged 22 to 31 years old (nine males and one female, mean age = 25.7 years, SD = 2.8 years). All participants had normal or corrected-to-normal vision with no other physical impairments. None were from the medical school and thus all participants had no surgical experience.

B. Apparatus

A laparoscopic simulated trainer developed for the present study was shown in Fig. 1. Pointing movements were performed holding a laparoscopic instrument (ENDO SHEARS 5 mm 3/4" Curved Scissors, Autosuture) through a rubber diaphragm used as the patient' abdominal wall. A horizontal occluding board prevented direct vision of the instrument displacement during performing tasks. However, participants could control the trajectory of the instrument visually through the video screen located at 90 cm from the body. A digital camera record instrument displacement movement and the latter was visible continuously and in real time on the screen. By changing the camera zoom, the amplitude of the movement perceived on the video screen was changed. The whole experiment was controlled using a personal computer with a program developed in JAVA to set experimental parameters, give signals, and record data.

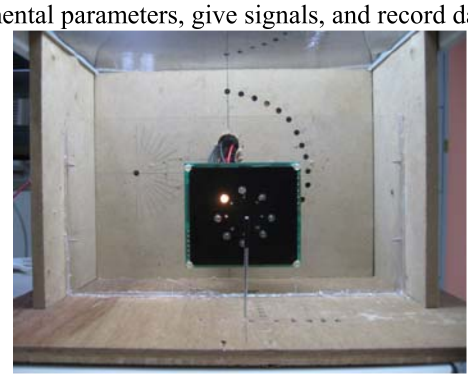

Fig. 1. The laparoscopic simulated trainer

C. Experiment design

Three within-subject factors were varied in the experiment, viz. magnification (three levels: low, medium, and high), movement amplitude between starting point and target (five levels: 24.24, 33.11, 42.38, 51.92 and 61.61 mm), and angle to the target from the center of the board (θ) [(eight levels: 0° (right), 45° (upper right), 90° (upper), 135° (upper left), 180° (left), 225° (lower left), 270° (lower) and 315° (lower right)]. Movement time (MT) and throughput (TP) were used as dependent variables. Movement time was measured in millisecond and throughput was calculated in accordance with the Equation (10) recommended by Soukoreff & MacKenzie [12]. The units of throughput are bits per second (or bps).

D. Procedure

Participants received practice trials before recorded movements to become familiar with the apparatus and to stabilize speed-accuracy trade-off of the movement.

Each condition was performed randomly as follows: participants stood in front of the laparoscopic simulated trainer and held the laparoscopic instrument with their right hand. The jaw tip of instrument was placed at the starting position and the position of instrument handle was adjusted to be close to subjects' elbow level to minimize discomfort and upper arm and shoulder muscle work [13]. At the beginning of each task, all of the eight signal LEDs lighting for 1 second to remind participants that the task will start. Subsequently, the movements were performed from the starting point to the target specified by signal LED. The LED did not turn off until the specified target was pointed correctly. There were ten pointing trials for each angular target. After the final specified target was pointed correctly, all the eight LEDs turned on to indicate that this magnification-amplitude condition was complete. Participants were instructed to reach the targets by making a three-dimensional movement in the trainer as quickly and accurately as possible. The time when the tip of instrument began to leave from the starting point was used as a criterion for movement onset, and when the tip of instrument reached the target, it was regarded as the end of pointing task. After completing each condition of task, the movement time was recorded for subsequent calculation and analyses

III. Results

A. Movement time

Mean movement time for the three magnifications, low, medium, and high, were 2476.0, 2266.1, and 2405.0 ms, respectively. There were significant differences between the magnifications in movement time ($F_{2, 10494} = 51.35$, $p < 0.01$). The movement time for the medium magnification was the fastest and the low magnification took the longest time. Further Duncan test showed that the movement time of the three magnifications were significantly different from each other.

There was a main effect of movement amplitude ($F_{4, 10494} = 35.50$, $p < 0.01$) on movement time. The movement time increased with the level of movement amplitude and the Duncan test result indicated that the movement time significantly differed from each other except the 33.11 and 51.92 mm.

There was a significant main effect of angle to the target ($F_{7, 10494} = 27.81$, $p < 0.01$). Based on the Duncan test results,

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a tendency was found for movement time to be longer for the left (180°) and lower right (315°) than for the six other conditions. Furthermore, the following comparisons were significant: movement time was longer for the 135° than for the 225, 0, 90, and 45; movement time was longer for the 270° and 225° than for the 45°.

B. Throughput

Throughput computed for the medium magnification at 2.7436 bps was the highest. For the low and high magnifications, they were 2.5496 and 2.5456 bps respectively. The ANOVA test result showed that the main effect of magnification was significant ($F_{2,\ 10494} = 37.23$, $p < 0.01$). Duncan test results indicated that the throughput for the medium magnification was higher than the low and high magnification statistically, but there was no significant difference between the low and high magnification.

There was also a significant throughput difference between movement amplitude ($F_{4,\ 10494} = 32.50$, $p < 0.01$). The throughput increased with the level of movement amplitude and the Duncan test result indicated that the movement time of the movement amplitude 51.92 mm was the highest and there were significant differences between three remaining movement amplitude groups.

There was a significant main effect of angle to the target ($F_{7,\ 10494} = 26.89$, $p < 0.01$). Based on the Duncan test results, it was found that the throughput for the upper right (45°) was the highest and for the left (180°) was the lowest.

IV. Discussions

A. Movement time

The analytical results of this study indicated that as the movement amplitude increased, movement time significantly increased, and vice versa. This outcome is in agreement with previous studies of Fitts' law published in recent decades [11, 14-16]. This finding also demonstrates that the movement time rises with the level of movement amplitude when a video-controlled pointing task with a long-shift laparoscopic instrument is performed.

However, it is noteworthy that the mean movement time of 2407.7 ms obtained in the present study is much higher than that observed when the movement was carried out either in the normal condition or in microscope work. Indeed, former experiments conducted in the directly visually-controlled condition showed that mean movement time was 345.2 ms for a laparoscopic instrument pointing [15] and was 476.9 ms for a long dowel pointing [14]. The movement amplitude of the former ranged from 140mm to 370 mm, and the latter values were refined from the conditions where the probe length = 40 mm and movement amplitude ranged from 100 to 400 mm. It is obvious that the movement amplitude of the present study was shorter but used a much longer movement time than that of these two studies.

In microscope work conditions, the mean movement time was 183.2 ms for Langolf, et al. [16] (where amplitude ranged from 2.5 to 12.7 mm) and was 676.1 ms for Langolf & Hancock [11] (where amplitude ranged from 2.54 to 7.62 mm). Under similar ranged movement amplitude, the mean movement time was approximately between 3.5 and 12 times longer than that of these two studies.

One possible reason for the discrepancy is the lack of accurate depth perception. When performing a three-dimensional pointing task through a two-dimensional image, in order to overcome this lack of depth perception, participants had to find the position of the instrument by touching the board that had attached targets and then moving the instrument jaw to touch targets along the board. As a result, pointing tasks that take seconds during direct visual feedback can take minutes during display control [7].

There were significant differences between the magnification levels in movement time, based on the analytical results. Movement time for the medium magnification was the fastest, and the low magnification took the longest time. These results are inconsistent with those of previous research. In the studies of Langolf & Hancock [11] and Ferrel, et al. [17], the results showed that magnification does not significantly affect movement time. However, the movement time significantly decreased as magnification levels increased in Ellis, et al. [18]. One possible reason for result discrepancies between the present and the three previous studies is due to the apparatus and tasks.

Unlike the studies where participants moved a part with a tweezer [11], performed tasks by holding a stylus along the horizontal plane [17], or carried out a Fitts' task on a PDA by manipulating a tele-robot [18]—the task of this study was to maneuver a long-shift laparoscopic instrument in a three-dimensional environment via two-dimensional video images. In contrast with those studies, it was more complicated and difficult for participants to adjust eye-hand coordination over this range without affecting their performance. For this reason, the magnification levels became a critical factor affecting the performance of pointing tasks. It was useful for participants to have a clear look at the targets and instrument jaw and to distinguish the relative position from them by magnifying the picture inside the laparoscopic simulated trainer. However, the movement time did not decrease with the level of magnification.

The movement time for three magnification levels revealed as a V-shape. A possible reason for resulting in this shape is the control-display gain setting. The gain settings involve a trade-off between gross-positioning time (getting to the vicinity of a target) and fine-positioning time (the final acquisition). With a high-gain (low magnification) setting, participants can quickly maneuver the instrument jaw to the vicinity of the target, but final acquisition of the target is exacerbated by the difficulty in precisely controlling the final position of the instrument jaw. Low-gain settings (high magnification), on the other hand, facilitate fine positioning of the instrument jaw, but increase the time to advance the instrument jaw over large distances [19]. Theoretically, the combination of gross positioning time and fine positioning time create a U-shaped influence in any given pointing task. In the present study, the medium magnification obtaining the lowest movement time seems to be an optimal tradeoff between the two types of movement.

The results of this experiment showed that the angle of approach significantly affects the time required to manipulate a laparoscopic instrument in a three-dimensional environment by monitoring two-dimension images. Further analytic results showed that movement times for movements along the four diagonals (45°, 135°, 225°, and 315°) were not significantly different from those for the two horizontal (0° and 180°) and two vertical (90° and 270°) directions. However, the following comparisons were significant: movement time was shorter for the right conditions (0°, 45°, and 315°) than for the left conditions (135°, 180°, and 225°); movement time was shorter for the upper conditions (45°, 90°, and 135°) than for the lower conditions (225°, 270°, and 315°). These tendencies may be attributed to the relative distance between targets and the entry portal. Because the entry portal was located at the right side for the right-handed participants, this setting consequently increased the distance to the lower and left targets. For this reason, it was observed that participants used more elbow extension for lower and left conditions than for upper and right conditions to make the laparoscopic instrument into the trainer. These results can be interpreted according to the results obtained in the study by Langolf, et al. [16], in which movement time and throughput for both the forearm and the wrist was lower than those for only the wrist.

B. Throughput

Based on the experimental results, the throughput had a tendency to increase with the level of amplitude. This implies that when the amplitude increases, participants have enough ability to process information produced by index of difficulty.

The average throughput (2.62 bps) obtained in this study is much lower than that observed in Lin, et al. [15], and in Baird, et al.[14]. Former experiments conducted in the directly visually-controlled condition showed that mean throughput was 8.43 bps for a laparoscopic instrument pointing [15] and was 8.06 bps for a long dowel pointing [14]. In comparison with the study where hand-pointing movement was visually controlled through a video display [17], the throughput estimated from the tenth trial for a block and a random trial presentation were 7.26 bps and 7.56 bps, respectively. These values are almost three times over that obtained in the present study. A brief summarization of these comparison results is that the information processing capacity of a video-controlled laparoscopic instrument pointing task is one-third of that obtained from a directly visually-controlled task with a long instrument or a video-controlled hand-pointing task. As described above, a possible reason for the discrepancy is the lack of accurate depth perception and limitations induced by instrument manipulation.

Generally speaking, the throughput under a given index of difficulty has a tendency contrary to movement time, meaning that higher movement time results in lower throughput, and vice versa. In magnification levels, the medium magnification seems to be an optimal tradeoff between the gross movement and fine movement, as the throughput for medium magnification was highest among the three levels. However, the throughput for the low and high magnification, considered as the two end points of the U-shaped influence, are not significantly different.

The results of this experiment showed that the angle of approach significantly affects the throughput of manipulating a laparoscopic instrument in a three-dimensional environment by monitoring two-dimensional images. Further analytic results showed that throughputs for movements along the four diagonals were not significantly different from those for the two horizontal and two vertical directions. However, the following comparisons were significant: throughput was higher for the right condition than for the left condition; throughput was higher for the upper condition than for the lower condition.

V. Conclusion

The present study aimed to investigate the essential characteristics of laparoscopic instrument movement control. Based on the experimental results, the following principal contributions can be drawn:

The magnification levels indeed affected the movement time and the throughput when performing video-controlled pointing tasks with a long hand-held laparoscopic instrument. However, the performance of video-controlled pointing tasks did not increase with the level of magnification due to the control-display gain setting. In the present study, the medium magnification obtained the lowest movement time, and the highest throughput seemed to be an optimal tradeoff between the gross-positioning and fine-positioning types of movement. Hence, this result suggests that surgeons should adjust the magnification level appropriately rather than excessively when moving the instrument during a laparoscopic surgery.

These experimental data also demonstrated that the movement time increased with an increase of movement amplitude during the performance of video-controlled pointing tasks. This finding, which was consistent with the previous two-dimensional or three-dimensional pointing-task studies, was not influenced by losing dimensionality of depth and two translational degrees of freedom.

The mean movement time of 2407.7 ms obtained in the present study is much higher than that observed when the movement was carried out either in the direct vision condition or in microscope work. The mean movement in this study was five to seven times longer, in comparison to those of directly visual studies, where the movement amplitudes were much longer than those in this study. In contrast with stereoscopic microscope work conditions, the mean movement time in this study was approximately between 3.5 and 12 times longer, even though under a similar range of movement amplitude.

In this study, movement time was discovered to be shorter for the upper and right conditions than for the lower and left conditions. The control performance was worst when moving to angles of 180° and 315°. This result suggests that surgeons should carefully consider the location of the entry portal to avoid involving these two movement angles in the laparoscopic surgery. These two angular movements may result in surgical risk to patients.

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