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TeleRobotic Fundamentals of Laparoscopic Surgery (FLS): Effects of Time Delay - Pilot Study

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Abstract— **Within the area of telerobotic surgery no standardized means of surgically relevant performance evaluation has been established. The Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) Fundamentals of Laparoscopic Surgery (FLS) program provides a set of standardized tasks that are considered the "gold standard" in surgical skill assessment. We present a methodology for using one of the SAGES FLS tasks for surgical robotic performance evaluation. The *TeleRobotic FLS* methodology is extendable to two other FLS tasks. Time delay in teleoperation in general and telesurgery in particular is one of the fundamental effects that limits performance in telerobotic surgery. In this pilot study the effect of time delay on the Block Transfer task performance was investigated. The RAVEN Surgical Robot was used in a master/slave configuration in which time delays of 0, 250, 500, and 1000 ms were introduced by a network emulator between the master (Surgeon Site) and the slave (Patient Site). The study included three subjects, each of whom was presented with three of the four conditions. The results show that one subject had a lower error rate with increasing time delay, whereas the other subjects had a higher error rate with increased delay. The subject with the longest average completion time suffered the least performance decrease under time delay.**

I. INTRODUCTION

More precise, less invasive, and inherently safer techniques and equipment are a natural part of the evolution of healthcare. The Automated Endoscopic System for Optimal Positioning (AESOP) was the first robot approved for use in surgery by the US Food and Drug Administration (FDA). After its approval in 1994, the system assisted surgeons by supporting an endoscope and repositioning according to the surgeons' instructions [10]. Licensed by Computer Motion, Inc. (Goleta, CA), the AESOP was later incorporated into the Zeus robotic surgery system. The Zeus was used in the first transatlantic telesurgery, performed between Manhattan, New York, USA and Strasbourg, France in September 2001 [8]. The Zeus's major competitor was the da Vinci surgical robot, produced by Intuitive Surgical, Inc. (Mountain View, CA) and FDA approved in July 2000 [3]. In June 2003, the companies merged under the name Intuitive Surgical, Inc. and production of the Zeus and AESOP systems ceased.

Several surgical robotic systems are currently in development around the world. The system designed at the University of Tokyo [9] has performed telesurgical experiments throughout Asia. The NeuRobot from Shinshu University [4] has been used in clinical applications. Other systems include the University of Hawaii's, Teleoperated Robotic Surgery System [1], the MC^2E [13], and the University of Washington's RAVEN. With all of these systems, no standard means for surgically relevent performance evaluation has emerged.

The same was true in surgery until the late 1990s when the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) created a committee to develop curriculum for teaching the Fundamentals of Laparoscopic Surgery (FLS). The outcome was a curriculum that included both cognitive and psychomotor skills. The skills assessment consists of five tasks: Block Transfer, Pattern Cutting, Intracorporeal Knot Tying, Extracorporeal Knot Tying and Placement of a Ligating Loop. The FLS skills tasks have been validated to show significant correlation between score and postgraduate year [2]. These tasks have been used to quantitatively assess the skill of thousands of surgeons ranging from novice to expert and are considered by many the "gold standard" in surgical skill assessment. To move toward a standard for surgical robot evaluation and testing, we have adopted the FLS skills tasks. Initially, we are using the Block Transfer with the ability to add pattern cutting and intracorpreal knot tying as well.

The RAVEN Surgical Robot is a system designed for telesurgical applications. It consists of three main parts, the Patient Site (Fig. 1), the Surgeon Site and a communication layer connecting them [7]. Motion commands are transmitted from the Surgeon Site to the Patient Site via UDP/IP packets and video of the operative site is sent back from the Patient Site to the Surgeon Site. The communication layer can be any standard network configuration including local network, commercial Internet, wireless Internet or a combination of both. The RAVEN has been tested in a number of teleoperation modes including operating through a digital datalink onboard an unmanned aerial vehicle [6] and in the Aquarius Undersea Habitat [5]. The system has also teleoperated with the Patient Site our lab in Seattle, WA and the surgeon site located in Cincinnati, OH; Tokyo, Japan; Montpellier, France; and London, England connecting through commercial Internet.

In this paper we present a methodology for incorporating SAGES FLS Block Transfer task for telesurgical performance evaluation. We present results from a pilot study investigating effects of time delay on subject performance.

II. METHODS

A. Teleoperation

Real Teleoperation: In a real teleoperation, physical distance and a real network separate the patient and surgeon sites with time-varying delays. When a surgeon makes a

Fig. 1. The RAVEN Patient Site

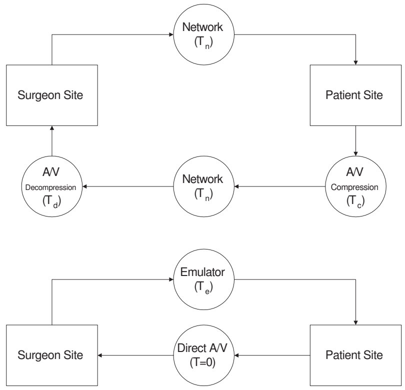

Fig. 2. Teleoperation communication flow

gesture using the master device, motion information is sent through the network to the Patient Site with a network time delay (T_n). The manipulator moves and the audio/video (A/V) device observes the motion. Digital A/V is compressed (T_c), sent from the Patient Site to the Surgeon Site through the network (T_n), then decompressed (T_d) and observed by the surgeon. The surgeon has experienced a total delay $T = 2T_n + T_c + T_d$, from the time he made the gesture to the time that action was observed. During teleoperation experiments between Seattle and the Florida Keys, $T_n \approx$ 75ms, and between Seattle and Italy, $T_n \approx$ 110ms [11]. Using a HaiVision Hai1000 $T_c \approx T_d \approx$ 120ms, using iChat $T_c \approx T_d \approx$ 500ms. Thus the total perceived delay varies between approximately 390ms and 1120ms.

Simulated Teleoperation: In the simulated teleoperation the Surgeon and Patient sites are not separated by physical distance but are connected through a Linux PC with two network cards running NISTNET that emulates a real network. This emulator allows the experimenter to adjust the average packet delay between the Surgeon and Patient sites [12]. The A/V feed is connected directly from a camera at the Patient Site to a monitor at the Surgeon Site through S-video eliminating any delay due to compression/decompression. The surgeon experiences a total delay, T_e due to the emulator, from the time he made the gesture to the time that action was observed. For this experiment delays of 0ms, 250ms, 500ms and 1000ms were used to approximate the range of delays experienced in real teleoperation.

The flow of information is illustrated in Figure 2. By setting $T_e = 2T_n + T_c + T_d$ one can simulate any real teleoperation condition. In this study, because the camera is connected directly to the monitor, there is no degradation of the video or audio signals due to compression techniques. Video degradation as a function of performance in telesurgery could be the subject of a future study, but is not a factor in this case.

B. Experimental Set-up and Subject Population

In this study, the Patient and Surgeon sites are located in the same room and are connected through the network emulator. The video feed comes directly from a Sony DCR-VX1000 3-chip digital video camera to a Sony Trinitron PVM-14M2MPU color monitor through an S-video cable.

Three subjects, non-surgeons, all right handed, two male and one female, ages ranging from 28 to 39, participated in this study under University of Washington Human Subjects Approval Number 01-825-E/B07. The subjects first performed training tasks in order to learn how to telemanipulate using the RAVEN. Within one week from the start of their training, they returned to perform the pilot study.

C. Training

Each subject received specific training on the system prior to the main study. Each subject watched an orientation video describing the RAVEN surgical robot and how to perform telemanipulation tasks. The video broke down manipulation into three parts: (1) positioning (2) orienting and (3) grasping, using first the dominant then the non-dominant hand. The subjects were instructed on three tasks (described below) that would enable them to sucessfully teleoperate using the RAVEN. Each task was performed until the subject's completion time for that task did not improve over three trials. Once the subject had completed a task they were allowed to move on to the next task. The subjects trained until they had completed all three tasks with both hands. The subjects then repeated the same training tasks under a time delay condition of 250ms. By first training the subjects with no-delay, they were able to learn the psychomotor skills necessary to telemanipulate objects under the most ideal conditions. By then repeating the training task under a delay condition, they learned to accommodate for delay. In order to reduce subject fatigue the non-delay and delay training were completed on separate days.

The training task board was built on a 4" x 2.5" piece of plexiglass. Six 1" x 1/4"-20 countersink screws were arranged in a grid of two rows of three and were capped by 1" pieces of 1/4" inner diameter rubber tubing. The tubes were arranged with 1" spacing between each of the three columns and 7/8" spacing between each of the two rows. Each of the six pegs were numbered 1-6 (see Figure 3). The following list describes the training tasks for the dominant hand. Tasks 1B, 2B and 3B, the tasks for the non-dominant hand are similar.

- *Task 1A: Dominant Hand Positioning* Using the dominant hand's tool, touch each peg in sequence 1 through 6 while keeping the non-dominant hand's tool in the field of view. You will know you've touched the peg when you see it deflect.
- *Task 2A: Dominant Hand Orientation* Using the dominant hand's tool, orient the grasper tips and place the tips into the center of each peg in sequence 1 through 6 while keeping the non-dominant hand's tool in the field of view.
- *Task 3A: Dominant Hand Grasping* Using the dominant hand's tool, open the grasper tips and place the tips with one jaw in the center of each peg and one jaw on the outside of the peg, then grasp the peg wall. Grasp each peg in sequence 1 through 6 while keeping the non-dominant hand's tool in the field of view.

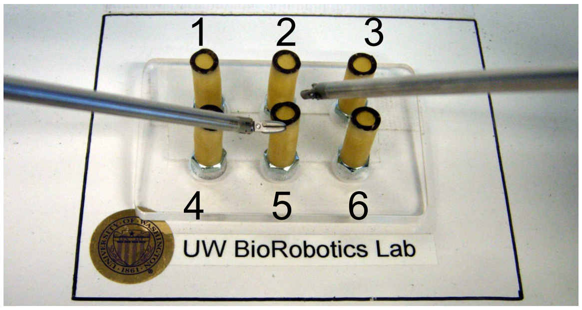

Fig. 3. Training Task Board

During the training or the study if the subject had been away from the system for more than 4 hours, they were required to warm-up for 5 minutes by performing the training tasks. The warm-up was performed with no time delay and subjects were allowed to move at their own pace.

D. Pilot Study

Three of the five SAGES FLS skills tasks (Block Transfer, Intracorporeal Knot tying, and Pattern Cutting) do not require specialized tools. For this study, the Block Transfer task was chosen. The task uses two graspers to move six blocks, one at a time, from the left side of the FLS peg board (Figure 4) to the right side, and then back to the left side. When moving from left to right, each block is lifted from the peg by the left hand, transferred in the air to the right hand, and then placed on the right peg. Hands are reversed when moving from right to left. One trial consists of moving all six blocks from left to right and then from right to left, for a total of twelve transfers. The time to move all six blocks in each direction was recorded, as was the time to move each block individually. Blocks were moved between specific pegs so transfer distances were comparable. Also recorded was the number of errors for each trial. An error is defined as dropping a block, whether recovered or not.

Each subject performed three repetitions of three delay treatments, for a total of nine trials. The three treatments included a delay of 0ms as well as two non-zero delays. The first, second, and third sets of three treatments each

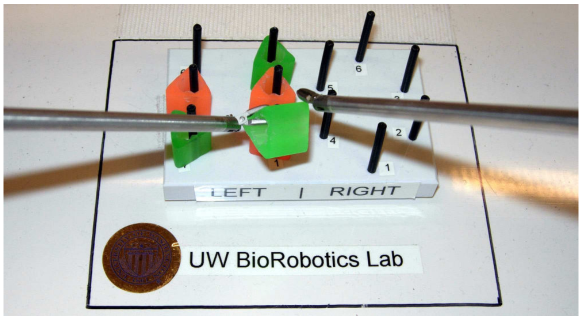

Fig. 4. The SAGES FLS Block Transfer task board set up with the RAVEN moving a block from left to right.

TABLE I

MEAN COMPLETION TIME FOR SINGLE BLOCK TRANSFER

Treatment - Delay (ms)	Mean Completion Time (sec)		
	Sub1	Sub2	Sub3
A - 0	41.68	49.85	120.38
B - 250	68.85	77.15	126.38
C - 500	n/a	121.77	170.40
D - 1000	140.96	n/a	n/a

consisted of one trial at each delay in pseudo-random order. The subjects were given a one minute break between each trial while the experimenter prepared for the next trial. After both the third and sixth trials, the subject was given a longer break. Though each treatment was presented in random order the delay condition was revealed before the trial. Informing the subject of the delay condition they would be operating under meant they could conciously accommodate for the delay condition just as they would if they were performing telesurgery on a patient. The experimenter was allowed to answer clarifying questions about the task, but was not allowed to coach subjects on strategies to approach the task.

III. RESULTS

The first subject performed the study using delays of 0ms, 250ms and 1000ms. It was determined after the first subject that 1000ms delay made the overall experiment prohibitively long and the subject commented on fatigue. The second and third subjects performed the study using delays of 0ms, 250ms, and 500ms. The first two subjects completed all nine trials for a total of 108 individual transfers. The third subject only completed five of the nine trials. The results listed are the mean completion time for a single block transfer based on the aggregate of the six blocks transferred from left to right and six from right to left per trial. Table I lists the mean completion time of each subject for each delay. Table II lists the percentage of errors of each subject for each delay.

A. Statistical Analysis

Multiple paired t-tests were conducted to see if there was a statistically significant difference in the mean time it took each subject to transfer one block. Differences were studied between different time delays (disregarding direction) and between directions within one time delay, for a total of six hypotheses per subject. For a single paired t-test, a value

TABLE II

PERCENTAGE OF BLOCK TRANSFERS THAT RESULTED IN ERROR (DROPPED BLOCK)

Treatment - Delay (ms)	Error rate		
	Sub1	Sub2	Sub3
A - 0	11%	11%	0%
B - 250	8%	19%	8%
C - 500	n/a	36%	8%
D - 1000	3%	n/a	n/a

TABLE III

P-VALUES FOR PAIRED T-TESTS. SIGNIFICANCE LEVEL OF $p < 8.333e-3$ REQUIRED TO SHOW SIGNIFICANT DIFFERENCE. *NOTE: SUBJECT 1 COMPARISONS SUBSTITUTE TREATMENT D FOR C

t-test	p-value		
	Sub1*	Sub2	Sub3
(A,B)	7.426e-8	9.420e-7	0.5322
(A,C)	<2.2e-16	2.583e-11	2.510e-3
(B,C)	1.032e-12	3.842e-6	4.529e-3
(Alr,Arl)	0.1913	0.0480	0.5219
(Blr,Brl)	0.4132	0.4091	0.3288
(Clr,Crl)	0.7681	0.5247	0.1844

of $p < 0.05$ is considered statistically significant. When multiple hypotheses are tested simultaneously, a Bonferroni correction is used. The Bonferroni correction states that if an experimenter is testing n independent hypotheses on a set of data, the statistical significance level that should be used for each hypothesis separately is $1/n$ times what it would be if only one hypothesis were tested. With $n = 6$ hypotheses, a significance level of $p < 0.05/6 = 0.00833$ is required. Table III sumarizes the results of the paired t-tests.

The statistical analysis shows that there was no significant difference between the mean block transfer time moving left to right and the mean block transfer time moving right to left for any subject at any delay level. There was a significant difference in mean block transfer time between delay levels for each subject, except Treatments A and B for Subject 3.

IV. DISCUSSION AND CONCLUSIONS

One might expect that as delay increases, so would the mean block transfer time. Subject 1 had the lowest mean block transfer times and also showed fewer errors as delay increased. Subject 1 commented that he was attempting to be more careful under longer delay conditions. Subjects 2 and 3 both had more errors with greater delay. Subject 3 did not show a significant difference in mean block transfer time between the 0ms and 250ms delay conditions. Subject 3 had the highest mean completion time at each delay level of the three subjects. The experimenters suspect that a subject who moves more slowly (and potentially more carefully) in the no-delay condition will suffer lower performance decreases as delay increases when compared with subjects who generally move faster. This hypothesis will be tested in future work.

We have presented an initial study using TeleRobotic FLS to evaluate task performance on the UW RAVEN Surgical Robot. Three non-surgeons performing a single task is not sufficent to draw definitive conclusions about the effects of time delay in telesurgery. This study has established a methodology for adapting the SAGES FLS skills tasks to telerobotic applications. Intracorporeal knot tying and pattern cutting are two additional FLS tasks that can be incorporated into the TeleRobotic FLS framework. A future study will include multiple surgeons with clinical robotic surgery experience on the ISI da Vinci. More detailed kinematic and dynamic data from the RAVEN will be analyzed to study the relationship between tool tip motion and completion time, and how these parameters are effected by constant or time-varying time delay.

V. ACKNOWLEDGMENTS

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