Using simulators to measure communication latency effects in robotic telesurgery

Roger Smith, PhD
Florida Hospital Nicholson Center
Celebration, FL
roger.smith@flhosp.org

Sanket Chauhan, MD
University of Minneapolis Medical School
Minneapolis, MN
sanket@umn.edu

ABSTRACT

Robotic surgical technology was originally developed by the US Army and DARPA as a tool to enable telesurgery at a distance. The Intuitive da Vinci system now provides a robotic surgical tool in a traditional operating room. But research continues into the extension of this capability to patients that are remote from the surgeon's location. In this paper we describe the interim results of experiments into the effects of communication latency in the safe execution of robotic telesurgeries. These experiments were carried out with the Mimic dV-Trainer, a simulator of the da Vinci robot, which was configured to insert defined levels of latency into the visual and command data streams between a surgeon and the operating field. Subjects were asked to perform four basic robotic surgical exercises. They were allowed to rehearse these in a zero latency environment and with a randomly assigned latency between 100ms and 1,000ms. Then each subject performed each exercise for measurement and analysis in our research.

This experiment measured the degradation of human surgical performance across a range of latency conditions. This paper reports on the comparison of the level of experience of the surgeons with their performance in a latency-effected environment. The data collected thus far refutes our hypothesis that more experienced surgeons would be more successful at managing the effects of latency and would perform better than those with less experience. Subjects in our experiment show no correlation between experience and successful performance under latency. The ability to manage latency in tele-operations may be shared between remote surgery and the control of a remotely piloted UAV's and UGV's. The results of our experiments may suggest that experience as a traditional pilot does not necessarily contribute to useful skills in flying UAV's or driving UGV's when latency is present.

ABOUT THE AUTHORS

Roger Smith, PhD, is an expert in the development of simulation devices and training programs. He has spent 25 years creating leading edge simulators for the Department of Defense and Intelligence agencies, as well as accredited methods for training with these devices. He is currently the Chief Technology Officer for the Florida Hospital Nicholson Center where he is responsible for establishing the technology strategy and leading technology implementation through the development of alliances with industry, the military, academic institutions, physician networks and governing medical associations. This includes identifying, executing and managing industry, military and federally funded simulation, modeling and training projects. He has served as the CTO for the U.S. Army PEO for Simulation, Training and Instrumentation (PEO-STRI); VP and CTO for training systems at Titan Corp; and Vice President of Technology at BTG Inc. He holds a Ph.D. in Computer Science, a Doctorate in Management, and an M.S. in Statistics. He has published 3 professional textbooks on simulation, 11 book chapters, and over 100 journal and conference papers. His most recent book is *Innovation for Innovators: Leadership in a Changing World.* He has served on the editorial boards of *Transactions on Modeling and Computer Simulation* and *Research Technology Management*.

Sanket Chauhan, MD, is a Robotic Urology Fellow at the University of Minnesota Medical School. Prior to this he was with the Florida Hospital, Global Robotics Institute and an instructor of Urology at the University of Central Florida's College of Medicine. Dr. Chauhan's research interests include developing new technologies for the future of surgery, telesurgery, surgical education, advanced surgical technologies, surgical simulation and the use of virtual reality and augmented reality in surgery. He has published more than 25 papers in peer reviewed journals and has authored 3 book chapters. Dr Chauhan is committed to surgical education using next generation VR based simulators. He is a member of the program committee for International Association for Science and Technology for Development (IASTED) Robotics and Control conference in 2010, and the World Robotic Surgery Symposium.

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BACKGROUND

Robotic surgery has been the topic of science fiction and scientific research for decades. As early as 1942, Robert A. Heinlein published the story "Waldo" in *Astounding Science Fiction*. He described the use of gloves and a harness to allow Waldo Jones to control mechanical arms of any size from large industrial and construction equipment to miniature tools for electronic and surgical work. The Industrial Revolution gave us many of the tools needed to extend the capabilities of the human body, but the Information Age gave us the computerized control systems necessary to effectively manipulate these devices. Surgical robots are a marriage of mechanical, electrical, optical, and software systems that can empower a human surgeon to peer into a patient's body with magnified stereo vision, probe the internal organs, and perform effective surgery without fully opening the patient's body.

In 1985, the PUMA 560 was used to accurately place a needle for a brain biopsy using CT guidance (Kwoh et al, 1988). In 1988, the PROBOT at Imperial College London, was used to perform prostate surgery. In 1992, Integrated Surgical Systems introduced ROBODOC to mill precise fittings in the femur for hip replacement. Intuitive Surgical leveraged the research work of the Defense Advanced Research Projects Agency (DARPA) and used those technologies to create the da Vinci Surgical System which they introduced in 1997. Computer Motion followed a similar path and fielded the AESOP and ZEUS robotic systems (Figure 1), which were later acquired by Intuitive Surgical (Satava, 1998; FDA, 2005).

Figure 1. ZEUS Surgical Research Robot

Intuitive Surgical's da Vinci robot is currently the only FDA approved device for robotic surgery on human patients. This system senses the surgeon's hand movements and translates them into scaled-down micro-movements to manipulate tiny instruments inside the body. It also detects and filters out any tremors in the hand movements, so that they are not expressed robotically. The camera used in the system provides a true stereoscopic picture transmitted to and viewed through a surgeon's console (Figure 2).

These devices opened the door for the realization of surgery-at-a-distance, a.k.a. telesurgery, in which a surgeon is able to extend his reach and perform surgical procedures at a significant distance from the patient. This capability has been demonstrated under unique conditions by multiple experiments (Himpens, 1998; Janetschek, 1998; Fabrizio, 2000; Sterbis, 2007). Our research project at the Florida Hospital Nicholson Center is demonstrating the maturity of the existing telecommunication infrastructure within a hospital system to support daily, on-demand telesurgery right now. Our experiments are based on the da Vinci surgical robot (Intuitive Surgical, Inc.) and the dV-Trainer simulator (Mimic Technologies, Inc.).

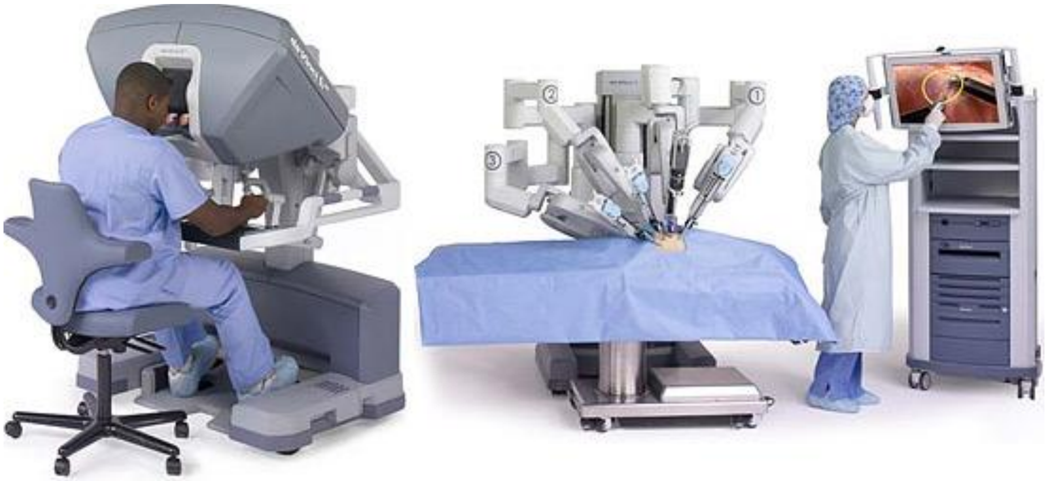


Figure 2. da Vinci Surgical Robot (Intuitive Surgical, Inc.)

METHODS

We explore the effects of communication latency on surgeon performance. This latency effect is created using the dV-Trainer simulator (Figure 3) of the da Vinci surgical robot (Hung, 2011; Kennedy 2009). The simulator allows the insertion of specific levels of controlled latency so that the user's physical movements are not manifest by the simulated instruments until after the defined latency period has elapsed.

Figure 3. dV-Trainer Simulator (Mimic Technologies, Inc.)

During actual telesurgery, the messages sent between the surgeon's machine and the remote patient station will be delayed due to the speed of light and the message routing that occurs on the internet. Determining how much latency can be safely tolerated in surgery is an important question (Anvari, 2005 and 2007). This experiment hypothesizes that there are two distinct thresholds of performance under increasing latency. The first is the level of latency at which a surgeon can first detect that his or her movements are being affected by the communication link. Any communication latency lower than this level is imperceptible and potentially non-invasive to the surgical procedure. Hence, if such levels can be achieved in the real world, then telesurgery may be safe for human surgery right now. The second level is the point at which the surgeon's performance is degraded to the point that the surgery cannot be performed safely (Marescaux, 2002; Lum, 2009). This level is identified through both simulator measured performance and the expert opinion of the surgeon. Between the first and second thresholds, a surgeon may be able to successfully control the effects of latency and perform a safe and successful procedure. Beyond the second threshold, telesurgery would be considered unsafe with the available equipment (Figure 4).

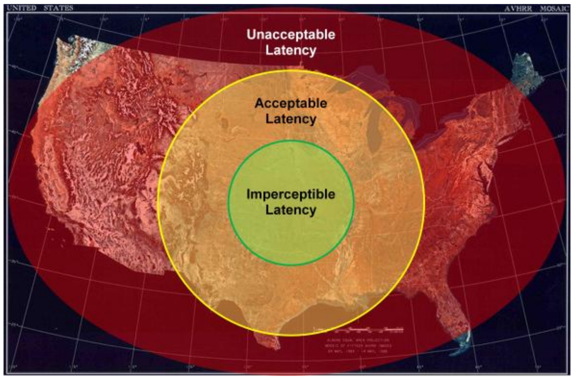
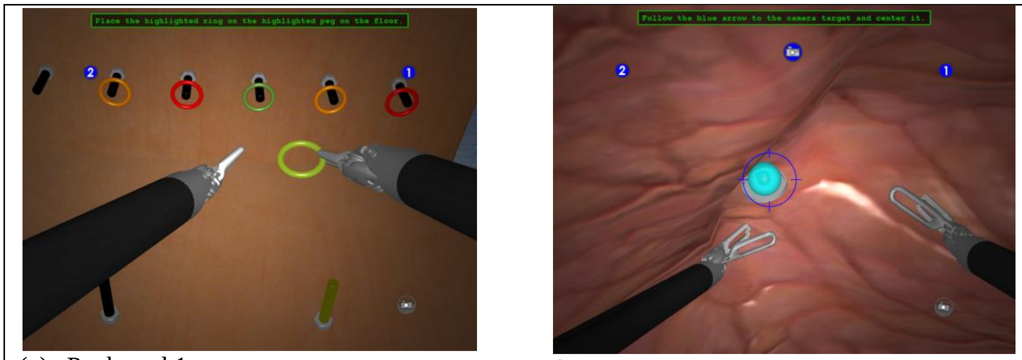
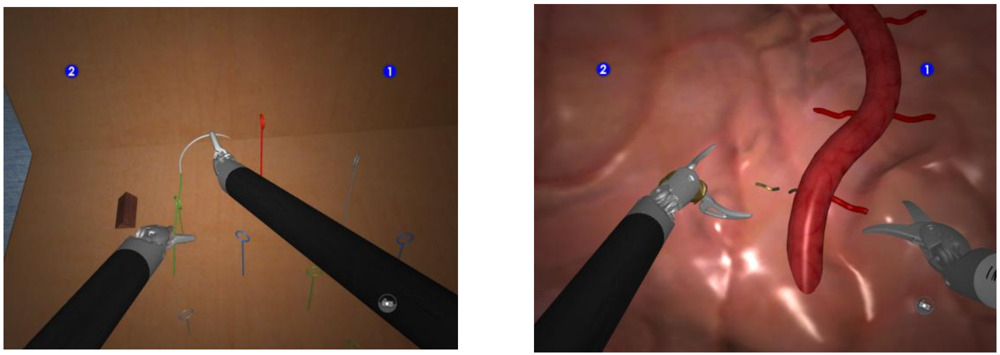


Figure 4. Conceptual Diagram of Communication Latency Thresholds.



(a) Pegboard 1 (b) Camera Targeting



(c) Thread the Rings (d) Energy Dissection

Figure 5. Simulated Surgical Skills Tasks

We further hypothesize that more experienced surgeons will be more successful at managing the effects of latency and would be the best practitioners for this extension of robotic surgery. If this hypothesis is correct, then surgeons with more experience should achieve higher scores and shorter completion times in the simulation experiment that we are performing. This paper reports on the analysis of this specific question comparing surgeon experience to the ability to successfully manage the effects of latency.

In this experiment, subjects performed the four simulated surgical skills exercises shown in Figure 5. These represent many of the core skills that are required in robotic surgery. Each subject performed each exercise three times. First, the subject was given an opportunity to perform the task without any imposed latency. This baseline insured that they were able to successfully operate the controls under normal conditions. Second, they were allowed to perform each of the four exercises at their randomly assigned latency level. These repetitions provided the learning necessary to achieve a sustained level of proficiency within a latent environment (Rayman et al 2006). Finally, each subject performed all four exercises at the same randomly assigned latency level and their performance was measured for analysis in the study.

A single, constant latency level between 100 milliseconds (ms) and 1,000ms at increments of 100ms was randomly assigned to each subject (e.g. 100ms, 200ms, 300ms. 400ms, etc.). A proctor was available to instruct subjects in the use of the equipment and to guide them through the curriculum of the protocol. However, this proctor was not allowed to give suggestions on performance of the exercises or to tell the subject the specific level of latency that they were experiencing.

Data Collection

Experimental data was collected by the simulator software and manually via questionnaires. Research proctors administered a Pre-Test questionnaire on the level of surgical experience and related activities of the subject. All personal and performance data was anonymized to insure that the identity of the subject could not be linked to the data that was collected. The proctors also administered a Post-Test questionnaire at the conclusion of each of the skills exercises during the final performance stage. The simulator software automatically collected multiple measures of the subject's performance. This provided data for all subjects at zero latency, during their familiarization stage with latency, and during the final stage which is the focus of the analysis. This data will allow us to perform multiple analyses of the skills of robotic surgeons both with and without communication latency, which will be published in future papers.

Pre-Test

The Pre-Test questionnaire identified multiple items of demographic, experience, and practice data on the subjects. These included: age, gender, dominant hand, surgical status, years of surgical experience, years of laparoscopic experience, years of robotic experience, number of weekly procedures in laparoscopy and robotics, and experience with laparoscopic and robotic simulators, as well as with video games and musical instruments. Additional questions captured their opinion on the use of simulation in surgical education and certification.

This data was then matched to the data from their performance in the simulator.

Simulator Performance

During the experiment, the simulator itself collected a number of data points on each subject's performance. These included: time to complete, overall score, total hand motion in centimeters, master working space, number of instrument collisions, number of items dropped, excessive instrument force, distance instruments out of view, incorrect use of electrical energy, simulated blood loss, and number of broken blood vessels.

Post-Test

As the subjects completed their final repetition of each of the four skills exercises, the proctor administered a post-test questionnaire which asked the subject for their opinion on the stress induced by the simulation with latency. This included measures of the mental and physical demands of the task, the pace of the task, their opinion on their level of success, the amount of effort expended, the level of mental discouragement experienced, and their perceived complexity of the exercise.

RESULTS

This paper reports on the analysis of data from the first 54 subjects in the study. Of the 54 subjects who began the experiment, several were unable to complete all of the tasks due to the limited amount of time that they could devote to the experiment. Others found the experiment too taxing and elected to terminate their participation before completion. As a result, we collected complete data sets without latency on 42 subjects and complete data with latency on only 21 of those subjects.

This data was analyzed to determine the level of correlation between the subjects' experience and their performance both with and without latency. For the non-latency sample size of 42 and $\alpha=0.05$, the Pearson Product Moment Correlation (PPMC) value is 0.304. This means that for a correlation coefficient of two variables in this size of sample to be significant, it must be larger than the PPMC value.

Table 1. Correlation Coefficients without Latency

Exercise	Overall Score	Time Complete
Pegboard 1	0.141	-0.110
Camera Targeting	0.201	-0.173
Thread the Rings	0.156	-0.225
Energy Dissection	0.267	-0.217

In an environment without any latency imposed we found a positive correlation between years of robotic experience and overall performance score, as well as a negative correlation between experience and the total time to complete the exercise (Table 1). Though this correlation is consistently supportive that surgeons with more experience perform non-latency exercises better than those with less experience, the degree of this correlation is not large enough to be statistically significant for this sample size.

When latency is added, a simple correlation coefficient is not sufficient for analyzing the effect of robotic experience on performance. Each subject received a randomly assigned latency, of which there were 10 possibilities. Within the current sample, we have between 0 and 5 subject data points at each latency level. Therefore, under latency, we examine the data by visual examination of a multiline scatter plot.

Scatterplots can illustrate the linear relationship between two variables in the model. Without latency, a relationship can be seen for both overall performance score and time to complete the exercise (Figures 6 & 7). However, when latency is present, the plots show that there is not a relationship between the two variables for the subjects tested (Figures 8 & 9).

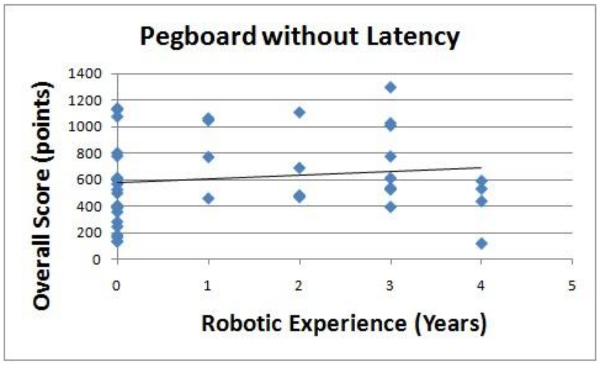


Figure 6. Correlation between Robotic Experience and Overall Score for the Peg Board exercise without communication latency.

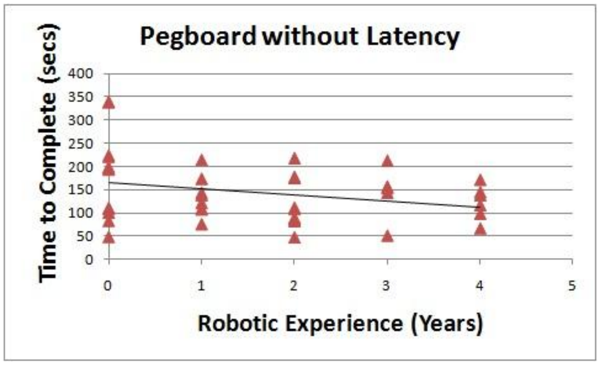


Figure 7. Correlation between Robotic Experience and Time to Complete for the Peg Board exercise without communication latency.

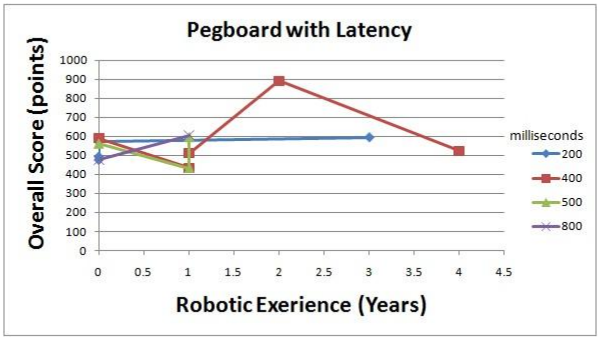


Figure 8. Correlation between Robotic Experience and Overall Score for the Peg Board exercise with various communication latencies.

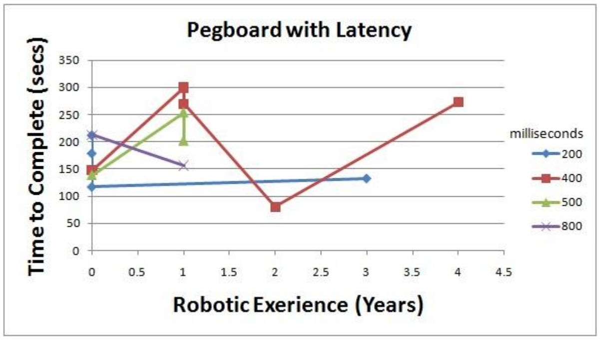


Figure 9. Correlation between Robotic Experience and Time to Complete for the Peg Board exercise with various communication latencies.

The data suggests that surgeons who have more experience in robotic surgery are not better equipped to self-manage the challenges presented by communication latency in telesurgery. Subjects with little experience are as likely to successfully manage latency as are surgeons with more experience.

This same trend holds when comparing independent variables like total surgical experience and laparoscopic experience to the scores achieved in the simulator with latency.

CONCLUSIONS

The lack of correlation between experience and telesurgical performance under latency refutes our original hypothesis that a more experienced surgeon would more successfully manage the effects of latency. This negative finding has led to speculation on the cause of these results. Several may be possible, but each will require additional experimentation. First, experienced surgeons may be very talented, but fixed, in their methods of performing surgery. This may lead them to perform poorly under latency because it is difficult for them to modify their behaviors, where inexperienced surgeons are less ingrained and more adaptable to the situation. Second, since the simulator is a computer-generated virtual environment, it is possible that surgeons who have more experience in simulators, virtual worlds, and computer games may have developed a proficiency for solving problems in this kind of environment. They may also have experienced latency in those environments and developed techniques for compensating for it. Third, the ability to manage latency may be related to the physical and biological wiring of an individual. This could be a similar phenomenon to the tendency for some people to experience simulator sickness, while others do not suffer from it. These speculations are worthy of further investigation.

The objective of this analysis was to identify the degree to which a surgeon can compensate for the effects of latency that are present in a telesurgery environment. The long-term goal is to identify the thresholds where safe and successful surgery can be performed. Our findings at this point refute our hypothesis that more experienced surgeons would be able to manage latency more successfully. In the data collected there is no correlation between robotic experience and the ability to achieve a higher score in the simulator when latency is inserted into the procedure.

These results may inform research on remote teleoperation in other environments, such as the control of UAV's and UGV's. Experienced pilots and vehicle drivers may not be better equipped to manage the effects of latency than pilots/drivers with less experience. Other factors may be more important in predicting a person's ability to tele-operate a remote system successfully. The similarity between remote surgery and remote vehicle operation is speculative and would require specific research experiments with those systems to verify.

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