2008

ROBOTIC TELESURGERY: AN INVESTIGATION OF UTILITY, HUMAN ADAPTATION, AND PERFORMANCE

Reiza Rayman
Western University

ROBOTIC TELESURGERY: AN INVESTIGATION OF UTILITY, HUMAN ADAPTATION, AND PERFORMANCE

(Spine title: Robotic Telesurgery)

(Thesis format: Integrated-Article)

by

Reiza Rayman

Graduate Program
in
Medical Biophysics

A thesis submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

THE UNIVERSITY OF WESTERN ONTARIO
School of Graduate and Postdoctoral Studies

CERTIFICATE OF EXAMINATION

Supervisor	Examiners
Dr. Serguei Primak	Dr. Jeff Carson
Supervisory Committee	Dr. Ian MacDonald
Dr. Aaron Fenster	Dr. Ken McIsaac
Dr. Rajni Patel	Dr. Garnette Sutherland
Dr. Terry Peters	
Dr. Richard Novick	

The thesis by

Reiza Rayman

entitled:

Robotic Telesurgery: An Investigation of Utility, Human Adaptation, and Performance

is accepted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Date____________________________

Chair of the Thesis Examination Board

ABSTRACT

Robotic surgery is a powerful, new method for performing minimally invasive surgery (MIS). The method allows complex procedures through incisions which are 10 mm or less. Robotic surgery has grown rapidly because small MIS incisions result in rapid patient recovery compared to conventional methods.

Although surgical robots have the potential of long distance control, insufficient data is available to determine whether long distance robotic surgery, or telesurgery, is practical. Telesurgery could provide multiple benefits, including dissemination of expertise, widespread patient care, cost savings, and improved community care.

We describe a series of experiments to investigate telesurgery using a one of a kind telesurgery platform and ground- and satellite-based Internet networks. The networks provided the redundancy and quality of service that would be required for human surgery.

Tolerances for performing surgical tasks over a long distance were unknown. We show that operators using the platform can complete dry lab manoeuvres with communication latencies up to 500 ms, with no appreciable increase in error rates. Such latency would be equivalent to a North American transcontinental distance, implying a wide range of telesurgical capability.

The characteristics of ground- and satellite-based Internet networks for telesurgery were unavailable. We demonstrate that emulated surgery in animals can be effectively performed using either ground or satellite. The networks can reliably support surgery, and satellite-based surgery can be performed even though latency exceeds 500 ms. Further, satellite bandwidth should be above 5 Mb/s for telesurgery applications. Satellite networks could be used either for back up or primarily where a community does not have ground-based equipment.

Methods of training operators for telesurgery had not been explored. We demonstrate two methods of training for telesurgery. Operators doing dry lab surgical manoeuvres performed equally well either with sequentially increasing latency or with full latency only, suggesting that both methods of training may be effective.

Telesurgery can become a practical method of treatment. Within a few years, more widespread platforms and telecommunications may exist to launch everyday telesurgery procedures.

Keywords: Telesurgery; telemedicine; robotics; surgery; latency; satellite; Internet; remote care

Co Authorship

The following thesis contains published material.

Permission to reproduce the articles published by The International Journal of Medical Robotics and Computer Assisted Surgery appears in Appendix B.

Chapter 2 has been published in The International Journal of Medical Robotics and Computer Assisted Surgery as "Long-distance robotic telesurgery: a feasibility study for care in remote environments" by R Rayman, K Croome, N Galbraith, R McClure, R Morady, S Peterson, S Smith, V Subotic, A Van Wynsberghe and S Primak. I developed the telesurgery network in consultation with industrial partners. I designed and performed the experiments as one of the subjects, interpreted the results, and wrote the manuscript. All these activities were performed under the supervision of Serguei Primak.

Chapter 3 has been published in The International Journal of Medical Robotics and Computer Assisted Surgery as "Robotic telesurgery: a real-world comparison of ground- and satellite-based Internet performance" by R Rayman, K Croome, N Galbraith, R McClure, R Morady, S Peterson, S Smith, V Subotic, A Van Wynsberghe, R Patel and S Primak. I developed the telesurgery network in consultation with industrial partners. I designed and performed the experiments on the robotic console, interpreted the results, and wrote the manuscript. All these activities were performed under the supervision of Serguei Primak.

Dedicated to

My family and wife Jennifer who offered unconditional support

throughout my studies

and to

My many colleagues who have encouraged and

inspired me to follow the path less taken.

Acknowledgements

I would like to thank several individuals and organizations for their support and contributions to this work. Thanks to:

- My supervisor, Dr. Serguei Primak, for providing support and advice throughout my thesis work and beforehand. I am glad that we have been able to work so well together.

- My Advisory committee, Drs. Patel, Novick, Peters, and Fenster and to the entire CSTAR team.

- Intuitive Surgical Inc. for providing us with the ZeusTS platform, and agreeing to let it stay in London for further research.

- Bell Canada for their most generous support of this project. Their contribution to the research grants and to personnel was truly above and beyond my expectations.

- TeleSat Canada for generously supplying the satellite time and expertise. Again, the studies would not have been possible without this group.

- The Canadian Foundation for Innovation and The Ontario Research and Development Challenge Fund for supporting the initial research.

Contents

List of Tables

List of Figures

List of Appendices

List of Acronyms & Abbreviations

3D	Three dimensional
AESOP	Automated endoscopic system for optimal positioning
ANOVA	Analysis of variance
Gb/s	Gigabits per second
HCI	Human-computer interaction
ID	Index of difficulty
IMA	Internal mammary artery
IP	Internet protocol
IP	Index of performance
IP-VPNe	Internet protocol – Virtual private network

IT	Information technology
LAN	Local area network
LIMA	Left internal mammary artery
Mb/s	Megabits per second
MIS	Minimally invasive surgery
MT	Movement time
QOS	Quality of service
SAGES	Society of American Gastrointestinal and Endoscopic Surgeons
UDP	User datagram protocol
VPNe	Virtual private network
VR	Virtual reality

Chapter 1

1.1 Introduction

Robotic surgery overview

Robotic surgery is a new modality for minimally invasive surgery introduced over the past ten years. Minimally invasive surgery (MIS) involves the use of keyhole incisions to perform surgeries of the abdomen, chest, brain, or joints. By using a camera scope, MIS procedures are done with a video monitor. The camera, instruments, and other devices and introduced using hollow cylinders, or ports, placed through the body wall.

Until the advent of robotics, only simple MIS procedures could be performed. Dexterity, visualization, and instrument control were suboptimal with traditional MIS instruments, and did not allow procedures more complex than gall bladder removal to be done (1). With robotics, the surgeon is able to control multiple instruments from a console, and has superior, natural dexterity, while viewing a three dimensional image of the surgical site.

Robotics has revolutionized the surgeon's capability. Cardiac, lung, kidney, and prostate surgery can all be done using robotic MIS, and allows patients to recover much more quickly with decreased complication rates.

Robotic surgery systems have a master-slave architecture, with the surgeon displaced from the patient at a non sterile console. The surgeon sees the video and controls the robotic instruments from the console, thereby closing the control loop (figures 1, 2). The usual displacement between surgeon and patient is 5 – 10m. However, the extension of master-slave control to longer distances may introduce powerful, new capabilities.

Figure 1. The da Vinci surgical system. The surgeon controls robotic instruments while sitting at a console in an unsterile area of the operating room. A bedside surgeon and scrub nurse assist with external arm adjustments, instruments changes, or port placement changes. (Source: Media courtesy of Intuitive Surgical Inc.).

Figure 2. The surgeon operates while viewing a three dimensional image of the surgical site at the console. The thumb and index finger are used to control the robotic instruments. Each robotic instrument has seven degrees of freedom motion – three translational planes plus pitch, yaw, roll and open/close at the end effector. (Source: Media courtesy of Intuitive Surgical Inc.).

The use of robotics is continuing to expand quickly. As patients benefit from MIS techniques for an increasing scope of procedures, the acceptance of robots in the operating room is becoming widespread (2). Early experience with robotics focused on procedure development and safety. This eventually led to the expansion of the field.

1.1.2 Early experience

The first robots began to enter the operating room in the late 1990's. Robots had not been experienced by surgeons, hospitals, or health regulatory bodies. As a result, only the least invasive and least costly units began to get a foothold in academic centres.

The first widespread, commercially available robot was the AESOP (automated endoscopic system for optimal positioning; Computer Motion Inc. circa 1995). The AESOP was a one armed robot capable of holding and moving an endoscope under voice command of the surgeon. The AESOP system allowed the surgeon to perform MIS procedures without the assistance of a second surgeon to hold the endoscope. This change was invited, since holding an endoscope between the hands of the operating surgeon was both awkward and tiresome (figure 3).

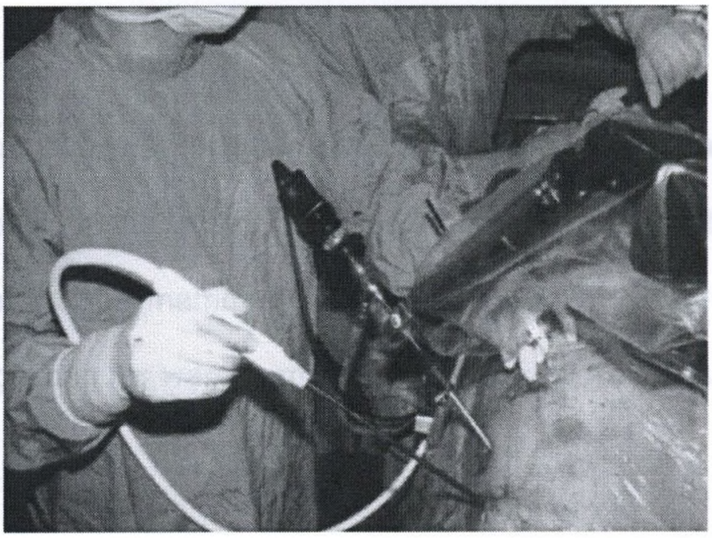

Figure 3. The AESOP robotic arm is shown in place during cardiac surgery. The arm holds the camera scope and is situated between the left and right instrument ports (the camera is seen as the black rectangular housing close to the surgeon's chest). The AESOP obviated the use of an assistant to hold the camera. Formerly, the surgeon's and assistant's arms would be overlapping.

The AESOP allowed further MIS procedural development. In cardiac surgery, the internal mammary artery could be harvested by coronary bypass surgery using endoscopic techniques (3). In obstetrics and gynaecology, several types of procedures could be performed by MIS without the use of an assistant surgeon and with improved operative time (4).

1.1.3 Procedural evolution

The introduction of three and four armed robotic systems (as shown in figure 1) occurred shortly after the AESOP had been approved for clinical use. Both the da Vinci (Intuitive Surgical Inc.) and Zeus (Computer Motion Inc. circa 1995) allowed the console surgeon to control camera movements and have full instrument control. Instruments could be changed 'on the fly' by the bedside surgeon during the procedure.

The development of new, more complex surgeries occurred hand in hand with regulatory approval. In the United States, a multi centre trial studied the safety of harvesting the left internal mammary artery for cardiac bypass surgery. In Canada and Europe, single centres were permitted to perform pilot studies in specific areas of practice.

The first fully endoscopic, robotic single coronary artery bypass surgery occurred nearly concurrently in Canada and Europe in 1999. In Germany, Falk and Diegler performed the procedure using the da Vinci robot, while Boyd used the Zeus system in London, Ontario (5, 6). Robotic cardiac procedures have continued to develop and are practiced in varying forms throughout North America and Europe (7, 8, 9). Additionally, other surgical specialties have developed robotic procedures which are beginning to show reproducible and improved patient safety, efficacy, and outcomes (10, 11).

1.1.4 Current trends

Robotic surgery has continued to evolve since its introduction. Currently, there are approximately 800 robotic units worldwide (12). Surgical robots have gone beyond the 'first adopter' stage and are steadily becoming an accepted device in most hospitals.

Medium to long term data have become available as the types and volumes of robotic surgery increase. In cardiac surgery, analyses of robotic bypass surgery (with or without concurrent stenting) are showing promising results (13 – 16). A learning curve analysis for these procedures has demonstrated a steep gain in knowledge, especially during the first 20 patients (17).

In general surgery, gallbladder and other biliary procedures have been safe and effective using robotic techniques (18, 19). While in urology, patients undergoing robotic radical prostatectomy have improved outcomes, decrease complication rates, with greater cost effectiveness (20). A consensus document recently released by the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) outlines key areas for the expansion of robotic surgery and telesurgery, including training and credentialing, risks and cost benefit analyses, and future research (21).

1.2 Telesurgery

Overview

The master – slave architecture of surgical robots leads to the question of long distance control. During robotic surgery, the operator sits at a console displaced several feet from the patient. There is a cable connection from the console to the robot providing real time video and commands. The displacement of the operator could also be several miles, or thousands of miles, if safety and effectiveness could be maintained.

The concept of long distance control would bear many benefits. An increase in the surgeon's 'range of ability' to operate could bring their expertise to a greater number of patients. Expert collaborations would be simpler, quicker, and more effective. Patient transportation costs would decrease. Under serviced or impoverished communities could be supported by established hospitals. Communications could even the playing field for healthcare, just as the Internet has done in other areas.

In this introductory section, telesurgery is defined. Earlier work in human performance study, long distance control, and medical teleoperation are discussed to provide a rationale for the development of a telesurgical testing and emulation described here. Further, the importance of training and a method of training evaluation are introduced.

1.2.2 Definitions

For the purpose of this thesis, we define telesurgery as the performance of surgery using a robot platform over a long distance communication link. This could occur within a city, between cities, or between countries. Here the surgeon is physically displaced from the operating room and the patient. Only a communication link connects the surgeon and provides interaction with the patient, instruments, and surgical team. The term 'surgery' within the definition means that the instruments are moved, controlled, and interact with the patient's body from a distance. It is not merely a remote observation.

The process of observing and providing advice or telestration from a distance is known as telementoring (22). This modality is quite useful for training or patient monitoring, however, it does not support surgery. Therefore, issues of communication delay, bandwidth, and other parameters are not as critical.

1.2.3 Human behaviour and computer machine interaction

Telesurgery is a complex interaction between a human operator and a robotic interface. Beyond empirical measurements, it is difficult to quantify or compare the performance of surgeons at a basic level, telesurgical or otherwise. Even simple manipulations can have many variables, confounding differences in surgical objectives, targets, and anatomies. Clearly, comparisons of performance need to begin with the simplest surgical movements, and must control all variables beyond those compared.

The earliest attempts at quantifying the interaction of human motor system with the environment occurred in the 1950's. Derived from the information theory of Shannon (23), Fitts considered the human motor system as an analogous extension of electronic signal propagation through a channel (24). Shannon's Theorem 17 expresses information capacity of a channel C as:

$$C = B\log_2 \frac{S+N}{N}$$

where the channel bandwidth is B;
the signal power is S;
and the noise is N.

Fitts suggested that information capacity could also flow through a human channel. He related to the earlier work of Shannon and conducted a series of experiments in which subjects performed simple, well practiced motor tests. In a reciprocal target tapping exercise, Fitts varied the target width W and the amplitude between targets A (figure 4). Average movement times were recorded along with the A and W combinations.

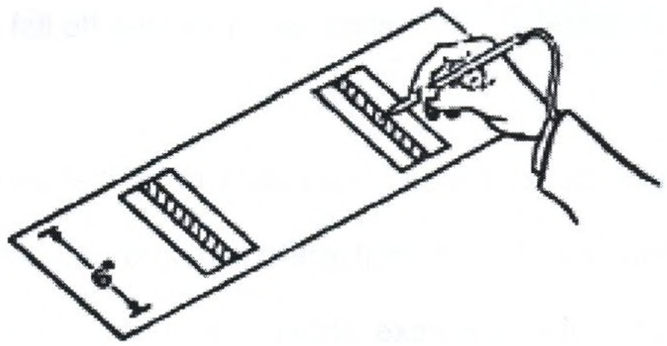

Figure 4. The reciprocal tapping exercise of Fitts' experiments. Subjects were asked to touch the targets with a stylus between the metal plates and to 'emphasize accuracy rather than speed.' Average movement time between the plates was recorded as well and the amplitude A between targets and the target width W. (Adapted from Fitts 1954).

Fitts surmised that the index of difficulty (ID) of such a task could be expressed in an analogous fashion to the signal to noise reasoning of Shannon, and stated that:

$$ID = -\log_2\left(\frac{W}{2A}\right) bits / response$$

Further, that the Index of Performance (IP) was an essential expression of the subject's performance rate, giving:

$$IP = -\frac{1}{t}\log_2\left(\frac{W}{2A}\right) bits / s$$

Within the exercises IP was relatively constantly over a certain range of difficulties, but then began to fall off outside these limits.

Since this original work, Fitts' law has been applied extensively within the field of performance and human computer interaction (HCI). MacKenzie and others have adapted Fitts' law to varying geometric exercises and tasks (25 – 27). A modification of Fitts' law to avoid negative ID values was suggested by this group, and is know as Shannon's modification:

$$ID = \log_2\left(\frac{A}{W} + 1\right)$$

Additionally, an adaptation of Fitts' law which includes latency has been suggested by others and will be discussed further (28, 29). The application of Fitts' law to telesurgery can be useful. In order to compare performance between groups, Fitts' law is used in this thesis to determine best methods of telesurgery training.

1.2.4 Considerations for long distance control

Applications for long distance control began as computer processing power and supporting technologies developed. In the aerospace industry, the issue of remote teleoperation has been pertinent for more than forty years. Methods of dealing with such delays range from ignoring the delay completely by allowing semi autonomy of the slave system, to predictive software and displays for 'man in the loop' tasks (30). Without any prediction, operators developed a 'move and wait' strategy in order not to create instability by overshooting.

Long distance control in which both visual and force feedback were provided have been studied (31, 32). If force is provided asynchronously from visual feedback, this could be counterproductive, since the operator would react to the force before an outcome was reached. This problem could be dealt with in two ways. Firstly, predictive methods were used to create stability of the long distance simulation (which spanned approximately 8000 km). Secondly, for unpredictable or disconnected communications, local supervisory control was introduced (31). The concept of shared control has also been supported and studied by others (33). In a different approach, impedance matching of position and force within a teleoperation test bed could overcome instability (32).

The concepts of prediction, autonomy, or shared control of teleoperation systems are quite removed from the current development of telesurgery. However, this work is presented within the context of this thesis as previously explored and having potential future telesurgery applications. Currently, telesurgery relies only on the raw data of the distant video source, and no predictive or other methods are employed.

1.2.5 Studies of medical teleoperation and learning

Prior to the availability of telesurgery platforms, several studies investigated the performance of surgeons during delayed teleoperation using box trainers or non surgical robots (34-37). Although these studies were conducted without clinical telesurgery platforms, the results are useful, since they simulate many of the tasks required during surgery (34). The amount of latency deemed as acceptable for telesurgery varied from 200 ms to 700 ms. Study differences included communications, user interfaces, surgical tasks, and methods of data collection. This earlier work can be used as a basis for conducting telesurgery with three or four armed robotic systems. None of the studies implemented predictive techniques nor shared autonomy, and most employed simulated communications networks.

Computer Motion Inc. (circa 1995) developed the first telesurgery capable three-armed platform. The ZeusTS telesurgery system was a prototype for proof of concept animal and human procedures. The system was a communications 'add on' which did not alter the architecture of the non telesurgery Zeus (38). Dr. Marescaux (Strasbourg, France) led the group through pilot animal telesurgery studies and one trans Atlantic patient gallbladder telesurgery procedure (39). Four surgeons performing gallbladder removal on pigs determined a qualitative cut off of 330 ms as a 'comfort zone' latency for telesurgery. They were unable to conduct a structured study of changes in performance because of equipment and time limitations. During the trans Atlantic case, a 10 Mb/s private network was used, providing a roundtrip delay of 155 ms. Since this was well below 330 ms, the procedure was easily done within a standard time. The authors acknowledged the studies as proof of concept only. They did not perform a structured analysis of latency, nor was the expense of the network considered.

The ZeusTS system was subsequently used by Dr. Anvari (Hamilton, Ontario) for testing of latency effects. Surgeons took significantly longer to complete dry lab exercises with simulated latencies above 500 ms (40). This provided a more structured analysis of acceptable latency than was previously available. However, due to the short duration of study, it was unclear whether short term learning or lack of equipment familiarization had confounded the results. Further work was done by this group on a series of patients (see section 2.7).

Concurrently, the use of the public Internet helped define how it could support telesurgery or related applications. A low bandwidth Internet connection can reliably identify anatomy during laparoscopic surgery (41). Experts could not tell the difference between local and remote still images. Additionally, a public Internet connection could be used to pre screen surgical candidates in third world countries studies and one trans Atlantic patient gallbladder telesurgery procedure (39). Four surgeons performing gallbladder removal on pigs determined a qualitative cut off of 330 ms as a 'comfort zone' latency for telesurgery. They were unable to conduct a structured study of changes in performance because of equipment and time limitations. During the trans Atlantic case, a 10 Mb/s private network was used, providing a roundtrip delay of 155 ms. Since this was well below 330 ms, the procedure was easily done within a standard time. The authors acknowledged the studies as proof of concept only. They did not perform a structured analysis of latency, nor was the expense of the network considered.

The ZeusTS system was subsequently used by Dr. Anvari (Hamilton, Ontario) for testing of latency effects. Surgeons took significantly longer to complete dry lab exercises with simulated latencies above 500 ms (40). This provided a more structured analysis of acceptable latency than was previously available. However, due to the short duration of study, it was unclear whether short term learning or lack of equipment familiarization had confounded the results. Further work was done by this group on a series of patients (see section 2.7).

Concurrently, the use of the public Internet helped define how it could support telesurgery or related applications. A low bandwidth Internet connection can reliably identify anatomy during laparoscopic surgery (41). Experts could not tell the difference between local and remote still images. Additionally, a public Internet connection could be used to pre screen surgical candidates in third world countries

(42). These types of studies helped to widen the scope of telemedicine and telesurgery, and prepare for regular long distance treatments. Recently, this group reported on a da Vinci prototype capable of telesurgery (Intuitive Surgical Inc.). Swine nephrectomy was performed over the public Internet using bandwidths of 3 to 8 Mb/s. All procedures were completed successfully, with latency ranging from 450 to 900 ms (43). The deliberation of the operator was important in successfully completing the tasks. The study did not conduct further structured tests for defining latency or bandwidth tolerances of the new system.

The introduction of supporting technologies for telesurgery is beginning. Xu et al. (44) have created a software routine which tracks the focus of the operator on the console screen. An attention map was constructed, and video outside the field of attention was smoothed to remove full details. While the area of attention maintained full detail, the video pre processing routine saved fifty percent of the bandwidth normally required. A telesurgery based orthopaedic robot which is capable of semi autonomous control has also been demonstrated (45). This type of advancement should continue to grow as more telesurgery capable robots are introduced.

1.2.6 Training, validation, and simulation

The training of personnel on robotic and telesurgery system will be important. While training in aerospace and other areas has been developed over several decades, training within surgery is much more basic. Surgeons have been trained to date using the apprenticeship model. A junior surgical trainee is paired with senior mentors, and learns by observation, graded tasks, and critical appraisals.

The apprenticeship model has worked over the years in conventional, large incision surgery, where observation, interaction, and shared control occur naturally. In a robotic system, training of junior residents would be difficult because the system is expensive and does not allow two people to interact directly on the patient.

Recently, training and simulation in surgery has begun for minimally invasive techniques. Guidelines have been provided for commercially available simulators based on the levels of validation proven for each (46). Two developing virtual reality (VR) simulators for MIS have shown face, content, and construct validity for varying aspects of each (47, 48). The use of VR training is an improvement over non computerized, 'box' trainers because VR methods provide more accurate metrics of performance and are more objective (49).

A good simulation tool must accurately represent the objects to be tested, must correctly test relevant tasks, and must distinguish those who are well trained from those who are not. Aspects of a valid simulation and methods of measurement have been described (50-53). Being able to validate new simulators in surgery will be important in the future. The utility of a simulator can only be proven by scientifically based validation methods (54). A breakdown of what constitutes a valid test is shown in figure 5.

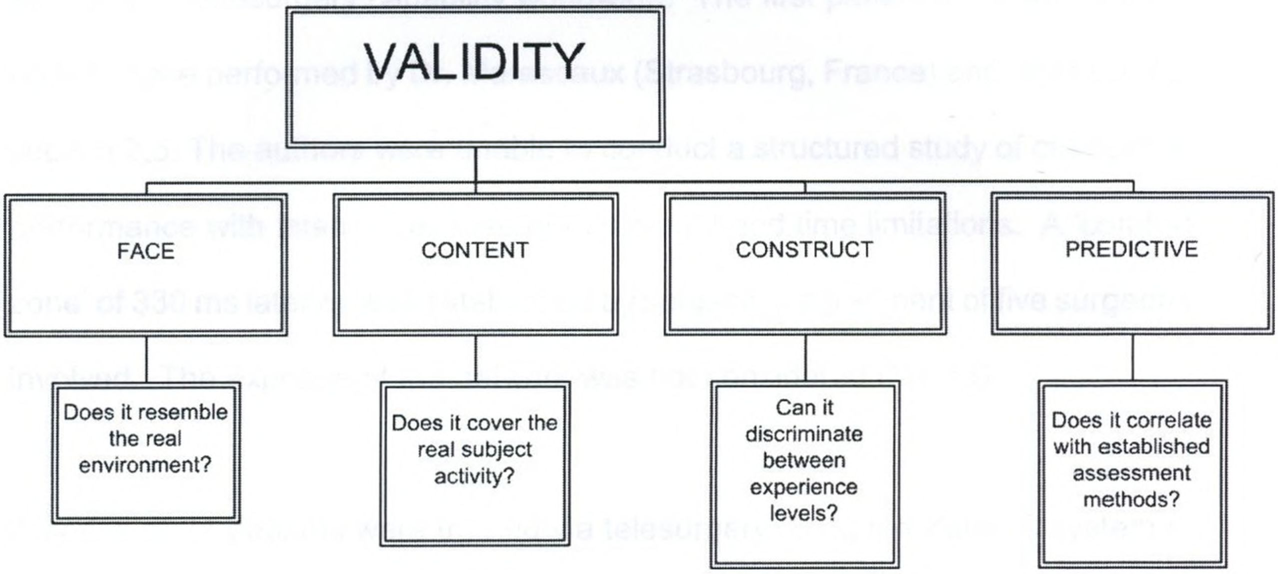

Figure 5. The key components of test validation and their basic definitions. Most papers describe experiments designed to provide construct validation of surgical simulators. Face and content validity are sometimes measured using structured questionnaires or expert opinions.

In addition to being valid, a good simulation should be reliable and transferable to the real environment (46). As robotic surgery and telesurgery grows, establishing new training methods will be significant. The apprenticeship model cannot support these new technologies, and a cost effective method is needed to prepare surgeons to use expensive and complex robotic equipment.

1.2.7 First patient telesurgery experience

The first patient telesurgery procedures were conducted between 2001 and 2003. At this time, the ZeusTS system had just been introduced. This was the first system with telesurgery capability worldwide. The first patient done was a trans Atlantic case performed by Dr. Marescaux (Strasbourg, France) and discussed in section 2.5. The authors were unable to conduct a structured study of changes in performance with latency because of equipment and time limitations. A 'comfort zone' of 330 ms latency was established by subjective agreement of five surgeons involved. The expense of the network was not considered (39, 55).

A series of 21 patients were treated via telesurgery using the ZeusTS system in 2003. The study patients underwent telesurgery for a variety of abdominal problems, and no complications were reported (56, 57). Communications used were a 15 Mb/s redundant virtual private network spanning 400 km in Ontario, Canada. The reported latency was 135 – 140 ms. The authors did not provide data regarding changes in performance with latency or bandwidth. A further expansion of a Canadian telesurgery network was promoted, however, this was not fulfilled due to the early stage of the research (58).

1.3 Research outline

1.3.1 Scope and rationale

Although teleoperation has been studied during the past 15 years, the field of robotic telesurgery is quite new (30). There is only one telesurgery robotic system worldwide. Although proofs of concept have been reported (38, 39, 55- 58), there is little quantitative data or performance measures available to optimize telesurgery. The benefits of this technique are multiple, including extension of surgical expertise, clinical collaboration, remote community care, transportation savings, and extended surgical training.

This thesis will concentrate on the investigation of telesurgery. Using a clinical grade telesurgery platform, its proposed set up, effects of varying communication parameters, surgical applications, and training will all be studied.

Telesurgery should be investigated using a step by step approach. Initially, system requirements and limitations need to be defined, with a focus on the effects of communication bandwidth and latency on performance. Secondly, an evaluation of the human operator in surgery should be done. Lastly, the training of telesurgery personnel and the impact of training will be important for the future practice of telesurgery. This training may differ from traditional methods, and will require special consideration.

1.3.2 Thesis objectives

The primary goal of this thesis is to define the requirements for telesurgery and identify its limitations. The main hypothesis is that telesurgery is clinically and technically possible. Thus, telesurgery can become a daily method of treating patients and expand the use of robotics. The three following objectives must be investigated to test this hypothesis:

1. Develop a network capable of supporting telesurgery and test limits of latency and bandwidth using this network.

2. Conduct emulated telesurgery on the network using realistic procedures, and compare ground and satellite network performance during the procedures.

3. Develop methods of training personnel for telesurgery, and compare the performance of trainees using these methods.

1.3.3 Thesis outline

The thesis goal is addressed within chapters two, three, and four in the form of two published papers and one paper submitted for publication. A conclusion of the results and future work is described in chapter five. A synopsis of the chapters and related hypotheses are found in the following sections:

1.3.4 Set up for telesurgery and its experimental investigation

Chapter 2 describes the communications network set up to test telesurgery. The ZeusTS system is used as the telesurgery interface. Subjects training with this platform are asked to perform dry lab tasks to simulate surgery at transmission latencies varying from 0 to 1000 ms. For this experimental set, latencies are simulated using network software. The hypothesis is that:

> *A reliable communication link with latency will allow the operator to perform basic maneuvers effectively. Performance will degrade or become impossible as latencies exceed 500 ms.*

It is shown within this chapter that telesurgery tasks using the test bed and ZeusTS interface were possible with latencies up to 1000 ms. Task performance did degrade above 500 ms when latencies were randomized. Both short and long term learning likely occurred over the four month test period.

1.3.5 Emulation and evaluation of basic clinical procedures

In chapter 3 long distance ground- and satellite-based telesurgery networks are used to perform surgery in live animals. Real surgery involves more complex movements and tissue interaction, and often requires increased cadence. It is unknown whether an operator is capable of the increased demand imposed by such procedures. Additionally, the behavior and reliability of ground- and satellite-based communications is assessed. In this set of experiments, the hypothesis is that:

> *Telesurgery will be possible in emulated clinical procedures. The land and satellite based Internet protocol communications can support telesurgery. Satellite based telesurgery may be impractical because signal delay is approximately ten times greater than land based and exceeds 500 ms. Satellite based telesurgery may not be possible below 5 Mb/s.*

It is shown within this chapter that both ground- and satellite-based telesurgery for the dissection of the left internal mammary artery (LIMA) in pigs was possible and not significantly different, even though satellite latency was approximately 600 ms. Additionally, a satellite bandwidth of at least 5 Mb/s was recommended for telesurgery.

1.3.6 Investigation of learning and training for telesurgery

In chapter 4 two methods of training telesurgery personnel are compared. Four surgical maneuvers are used for training subjects. The subjects experienced either a sequentially increasing latency from 0 to 700 ms during the training period, or 700 ms latency only. The performance of the two groups is compared. It is hypothesized that:

> *The training of subjects using a telesurgery simulator can show which methods are more effective. The approach to training may differ form traditional methods. Trainees experiencing 700 ms latency throughout all maneuvers will perform better than those training at zero latency and then adapting to the delay.*

It is demonstrated that either training with zero latency and then adapting to the delay, or training with full latency only produced equal performance. Both groups of subjects learned the tasks well, implying flexibility in training techniques.

References

[1] Berlinger N. Robotic surgery – Squeezing into tight places. N Engl J Med 2006; 354(20): 2099-2101.

[2] Donias H, Karamanoukian R, Glick P et al. Survey of resident training in robotic surgery. Am Surg 2002; 68: 177-181.

[3] Boyd D, Kiaii B, Kodera K et al. Early experience with robotically assisted internal thoracic artery harvest. Surg Laparosc Endosc Percutan Tech 2002; 12(1): 52-57.

[4] Mettler L, Ibrahim M, Jonat W. One year of experience working with the aid of a robotic assistant (the voice-controlled optic holder AESOP) in gynaecological endoscopic surgery. Human Reprod 1998; 13(10): 2748-2750.

[5] Rayman R. Robotic-assisted cardiac surgery. Surgical Innov 2004; 11(2): 73-79.

[6] Boyd D, Rayman R, Desai N et al. Closed-chest coronary artery bypass grafting on the beating heart with the use of a computer-enhanced surgical robotic system. J Thorac Cardiovasc Surg 2000; 120(4): 807-809.

[7] Srivastava S, Gadasalli S, Tijerina O et al. Planned simultaneous beating-heart totally endoscopic coronary artery bypass (TECAB) and percutaneous intervention in a single operative setting. Innovations 2006; 1(5): 239-242.

[8] Dogan S, Aybek T, Andreben E et al. Totally endoscopic coronary artery bypass with robotically enhanced telemanipulation: Report of forty-five cases. J Thorac Cardiovasc Surg 2002; 123(6): 1125-1131.

[9] Woo Y. Robotic cardiac surgery. Int J Med Robotics Comput Assist Surg 2006; 2: 225-232.

[10] Ruurda J, Wisselink W, Cuesta M et al. Robot-assisted versus standard videoscopic aortic replacement. A comparative study in pigs. Eur J Vasc Endovasc Surg 2004; 27: 501-506.

[11] Rockall T, Darzi A. Tele-manipulator robots in surgery. Br J Surg 2003; 90: 641-643.

[12] Harlin K. One company all but has a lock on robotic surgery equipment. Investor's Business Daily March 28, 2008.

[13] Boyd D, Kiaii B, Novick R et al. RAVECAB: improving outcome in off-pump minimal access surgery with robotic assistance and video enhancement. Can J Surg 2001; 44(1): 45-50.

[14] Boyd D, Desai N, Kiaii B et al. A comparison of robot-assisted versus manually constructed endoscopic coronary anastomosis. Ann Thorac Surg 2000; 70: 839-843.

[15] Boyd D, Kodera K, Stahl K et al. Current status and future directions in computer-enhanced and video- and robotic-assisted coronary bypass surgery. Sem Thorac Cardiovasc Surg 2002; 14(1): 101-109.

[16] Stahl K, Boyd D, Vassiliades T et al. Hybrid robotic coronary surgery and angioplasty in multivessel coronary artery disease. Ann Thorac Surg 2002; 74: S1358-1362.

[17] Novick R, Fox S, Kiaii B et al. Analysis of the learning curve in telerobotic, beating heart coronary artery bypass grafting: a 90 patient experience. Ann Thorac Surg 2003; 76(3): 749-753.

[18] Perez A, Zinner M, Ashley S et al. What is the value of telerobotic technology in gastrointestinal surgery? Surg Endosc 2003; 17: 811-813.

[19] Hourmont K, Chung W, Pereira S et al. Robotic versus telerobotic laparoscopic cholecystectomy: duration of surgery and outcomes. Surg Clin N Am 2003; 83: 1445-1462.

[20] Wolfram M, Brautigam R, Engl T et al. Robotic-assisted laparoscopic radical prostatectomy: the Frankfurt technique. World J Urol 2003; 21: 128-132.

[21] Herron D, Marohn M. A consensus document of robotic surgery. Surg Endosc 2008; 22: 313-325.

[22] Agarwal R, Levinson A, Allaf M et al. The RoboConsultant: Telementoring and remote presence in the operating room during minimally invasive urologic surgeries using a novel mobile robotic interface. Urology 2007; 70: 970-974.

[23] Shannon C, Weaver W. *The mathematical theory of communication.* 1949; Urbana: University of Illinois Press.

[24] Fitts, P. The information capacity of the human motor system in controlling the amplitude of movement. J Expt Psychol 1954; 47(6): 381-390.

[25] MacKenzie I. Movement time prediction in human-computer interfaces. *Readings in human-computer interaction (2nd edition). 1995; 483-493.*

[26] MacKenzie I. Fitts' law as a research and design tool in human-computer interaction. Hum-comput interact 1992; 7: 91-139.

[27] Accot J, Zhai S. Beyond Fitts' law: Models for trajectory-based HCI tasks. Proc SIGCHI Conf Hum Fact Comput 1997; 295-302.

[28] MacKenzie I, Buxton W. Extending Fitts' law to two-dimensional tasks. Proceedings of the CHI 1992; 219-225.

[29] MacKenzie I, Ware C. Lag as a determinant of human performance in interactive systems. InterCHI 1993; 488-493.

[30] Sheridan T. Space teleoperation through time delay: review and prognosis. IEEE Trans Robot Autom 1993; 9(5): 592-606.

[31] Andreu D, Fraisse P, Segovia De Los Rios J. Teleoperation over an IP network: from control to architectural considerations. 8th Internat Conf Cont Autom Robot Vis 2004: 765-770.

[32] Hirche S, Buss M. Study of teleoperation using realtime communication network emulation. IEEE AIM Conf 2003: 586-591.

[33] Bejczy A, Kim W. Predictive displays and shared compliance control for time-delayed telemanipulation. IEEE Intel Robot Syst IROS 90: 407-412.

[34] Perez M, Quiaios F, Andrivon P et al. Paradigms and experimental set-up for the determination of the acceptable delay in telesurgery. Conf IEEE EMBS 2007: 453-456.

[35] Hongo K, Goto T, Miyahara T et al. Telecontrolled micromanipulator system (NeuRobot) for minimally invasive neurosurgery. Acta Neurochir 2006; 98: 63-66.

[36] Kim T, Zimmerman P, Wade M et al. The effect of delayed visual feedback on telerobotic surgery. Surg Endosc 2005; 19: 683-686.

[37] Fabrizio M, Lee B, Chan D et al. Effect of time delay on surgical performance during telesurgical manipulation. J Endourol 2000; 14(2): 133-138.

[38] Butner S, Ghodoussi M. Transforming a surgical robot for human telesurgery. IEEE Trans Robot Autom 2003; 19(5): 818-824.

[39] Marescaux J, Leroy J, Gagner M et al. Transatlantic robot-assisted telesurgery. Nature 2001; 413: 379-380.

[40] Anvari M, Broderick T, Stein H et al. The impact of latency on surgical precision and task completion during robotic-assisted remote telepresence surgery. Comput Aid Surg 2005; 10(2): 93-99.

[41] Broderick T, Harnett B, Doarn C et al. Real-time Internet connections: implications for surgical decision making in laparoscopy. Ann Surg 2001; 234(2): 165-171.

[42] Lee S, Broderick T, Haynes J et al. The role of low-bandwidth telemedicine in surgical prescreening. J Pediatr Surg 2003; 38: 1281-1283.

[43] Sterbis J, Hanly E, Herman B et al. Transcontinental telesurgical nephrectomy using the da Vinci robot in a porcine model. Urol 2008; 71: 971-973.

[44] Xu J, Sclabassi R, Liu Q et al. Human perception based video preprocessing for telesurgery. 29th IEEE EMBS 2007: 3086-3089.

[45] Zhijiang D, Zhiheng J, Minxiu K. Virtual reality-based telesurgery via teleprogramming scheme combined with semi-autonomous control. 27th IEEE EMBS 2005: 2153-2156.

[46] Carter F, Schijven M, Aggarwal R et al. Consensus guidelines for validation of virtual reality surgical simulators. Surg Endosc 2005; 19: 1522-1532.

[47] Rosenthal R, Gantert W, Hamel C et al. Assessment of construct validity of a virtual reality laparoscopy simulator. J Laparoendosc Adv Surg Tech 2007; 17(4): 407-413.

[48] Verdaasdonk E, Stassen L, Schijven M et al. Construct validity and assessment of the learning curve for the SIMENDO endoscopic simulator. Surg Endosc 2007; 21: 1406-1412.

[49] Aggarwal R, Moorthy K, Darzi A. Laparoscopic skills training and assessment. Br J Surg 2004; 91: 1549-1558.

[50] Ahire S, Devaraj S. An empirical comparison of statistical construct validation approaches. IEEE Trans Engin Manag 2001; 48(3): 319-329.

[51] Hoyt W, Warbasse R, Chu E. Construct validation in counseling psychology research. Couns Psychol 2006; 34: 769-805.

[52] Moody L, Baber C, Arvanitis T et al. Objective metrics for the evaluation of simple surgical skills in real and virtual domains. Presence 2003; 12(2): 207-221.

[53] Gallagher A, Satava R. Virtual reality as a metric for the assessment of laparoscopic psychomotor skills. Surg Endosc 2002; 16: 1746-1752.

[54] Shavelson R, Stanton G. Construct validation: Methodology and application to three measures of cognitive structure. J Educ Measur 1975; 12(2): 67-85.

[55] Marescaux J, Leroy J, Rubino F et al. Transcontinental robot-assisted remote telesurgery: Feasibility and potential applications. Ann Surg 2002; 235(4): 487-492.

[56] Anvari M. Remote telepresence surgery: the Canadian experience. Surg Endosc 2007; 21: 537-541.

[57] Anvari M, McKinley C, Stein H. Establishment of the world's first telerobotic remote surgical service. Ann Surg 2005; 241(3): 460-464.

[58] *Telerobotics brings surgical skills to remote communities.* Lancet (editorial) 2003; 361: 1794-1795.

Chapter 2

Set up for telesurgery and its experimental investigation

Patient safety is paramount in any surgery, especially with new technology. Therefore, telesurgery must be reliable, robust, and redundant in order to minimize the probability of failure during a procedure. These characteristics apply to the entire system, including hardware, software, and communications.

Even if such criteria are met, basic surgical maneuvers may not be possible. Demands on the operator resulting from communications delay or inadequate bandwidth may be too high. The effect of these parameters on performance needs to be measured.

In these experiments, the set up for telesurgery and the effects of communication delay was investigated.

A version of this chapter has been published in The International Journal of Medical Robotics and Computer Assisted Surgery entitled:

"Long-distance robotic telesurgery: a feasibility study for care in remote environments" by R Rayman, K Croome, N Galbraith, R McClure, R Morady, S Peterson, S Smith, V Subotic, A Van Wynsberghe and S Primak.

2.1 Introduction

The use of robots in surgery is increasing, as the technology allows intricate procedures through port access incisions. For the past five years, surgeons have used robots to perform single coronary artery bypass, prostatectomy, and gastric fundoplication with 5 – 10 mm incisions. Surgical robots will continue to be used in more procedures as more powerful technologies are introduced.

Long distance robotic telesurgery is defined as the performance of surgery using a robot platform over a communication link. The remote surgeon sits at a central console, and performs surgery on a patient using a slave robot at a different location.

Robotic telesurgery has the potential to significantly improve healthcare in remote communities and provide cost effective services. Surgical care in remote or non-terrestrial environments will require sophisticated instruments, apparatus, and communications networks. In order to provide timely care, an expert surgeon could provide therapy to a patient thousands of miles away. Populations in remote environments may encounter variable surgical problems, and a variety of surgeons might be called upon to provide treatment or training to local medical crews.

The ability of the operator to overcome significant delays during surgery is unknown. Long distance surgery represents one of the most demanding multimedia applications to date, with little room for compromises in quality of service, or audiovisual fidelity. Additionally, the robotic platform would need to be highly ergonomic, and provide the surgeon with complete awareness of the patient's status.

Although teleoperation has been incrementally studied over the past fifteen years (1, 2), the field of robotic telesurgery is quite new. There is only one telesurgery capable, three armed robotic system worldwide. This system allows full robotic instrument and camera manipulation from the console, and places realistic surgical demands on the operator and the communications network. It is the only clinical grade, telesurgical robot in existence.

Our research group has now been provided with this robotic telesurgery platform. We are testing the platform in a stepwise process of discovery, with a focus on defining what can and cannot be done, especially with respect to limitations of latency, bandwidth, and platform architecture.

Using this platform, Butner and Ghoudoussi (3) provided qualitative insight into how much latency was comfortable for the surgeon. While 330 msec was the maximum latency recommended, they did not provide stepwise, quantitative information of telesurgical performance.

The work of Marescaux et al. (4) provided the first proof of concept that the system was capable of live patient surgery. Their trans Atlantic case on a female patient was conducted with latency of 155 msec, but they could not ethically perform varying latency experiments during this human procedure.

Anvari et al. (5) provided quantitative data of the impact of latency on performance of telesurgery for the first time. The group showed that operators using the telesurgery system required significantly more time to complete tasks as latencies approached 500 msec, with an associated increase in error rates. Similar results have been demonstrated with less sophisticated platforms (6, 7).

Human and technical limitations during telesurgery need to be defined. Moving forward, telesurgery could be applied to several scenarios, all with differing human resources, IT assets, and medical situations. Isolated environments such as Canadian or other remote communities, non terrestrial missions, or hostile (battleground) situations are all instances where telesurgery would provide valuable patient care. A basic set of rules should be applied to all scenarios based on these limits.

Our initial experiments were designed to test the feasibility of typical maneuvers during telesurgery. We used a novice group of operators to test both effectiveness at varying latencies, and to record any adaptation or learning which could occur.

Additionally, the reliability and flexibility of prototype telesurgery and IT equipment was tested. Based on these results, a set of recommendations for the advancement of telesurgery equipment has been derived.

2.2 Materials and Methods

Our group tested the feasibility of performing surgical maneuvers at varying time latencies. In remote environments, the latency of commands would be a significant and rate limiting factor in telesurgery. The perceived latency is the time difference between the surgical input by the operator at the console and the viewed manipulation (output) transmitted to the operator via remote camera.

In a communications network consisting of analogue to digital encoding, network transmission, and human reaction, the perceived time latency (T_P) is defined as:

$$T_P = T_{en} + T_t + T_r$$

where T_{en} is the time for encoding / decoding
T_t is the time for network transmission
T_r is the operator's reaction time to the output.

In a complex set of maneuvers meant to complete a task, the time to complete a maneuver (T_M) consists of the perceived time latency (T_P), plus the time for the maneuver displacement (T_{move}) and the time to interpret and plan the next input (T_{plan}):

$$T_M = T_{en} + T_t + T_r + T_{move} + T_{plan}$$

An overall task consists of many such maneuvers, each involving times for encoding, transmission, reaction, movement, and planning:

$$\begin{aligned} Task &= T_{M1} + T_{M2} + T_{M3} + \ldots.. \\ &= (T_{en1}+T_{t1}+T_{r1}+ T_{move1} +T_{plan1}) + (T_{en2}+T_{t2}+T_{r2}+ T_{move2} +T_{plan2}) + \ldots \\ &= \sum_{1}^{n} (T_{en} + T_t + T_r + T_{move} + T_{plan}), \qquad \ldots\ldots (1) \end{aligned}$$

where n is the total number of maneuvers required to complete the task. These parameters are interrelated, have effects on one another, and are affected by the performance of the system used and by the human operator (for example, a decrease in communications bandwidth would affect both transmission and interpretation and planning times). The implications and optimization of such a system will be discussed later.

We modeled surgical maneuvers using the following exercises. For each exercise, the task completion times and error rates were recorded.

2.2.1 Surgical exercises

The robotic exercises were designed to simulate typical surgical maneuvers. These involved object grasping and precise placement, object steering, and curved needle manipulation. We did not simulate more complex tasks such as knot tying or precise suture placement (figure 6). Our experiments were designed to determine whether even the simplest surgical tasks were feasible with signal delays. The experimental exercises were:

a) Pick up the orange cone with left hand and place in circle. Then replace to the original position with right hand. Pass back and forth six times;
b) Pick up a rod with left hand. Pass the rod through three hoops without touching the hoop. Pass back and forth through the hoops four times;
c) Pick up the orange ring with left hand, grasping the ring at the black line. Maneuver the ring with both hands so that right hand only holds it at the black line. Do not drop or ground the ring during maneuvering. Repeat back and forth four times;
d) Pick up a 6-0 needle with right hand. Pass needle to enter right dot and exit left dot. Retrieve exiting needle with left hand. Reload needle back to right hand and repeat six times. (Dexterity hand may be reversed for left handed people).

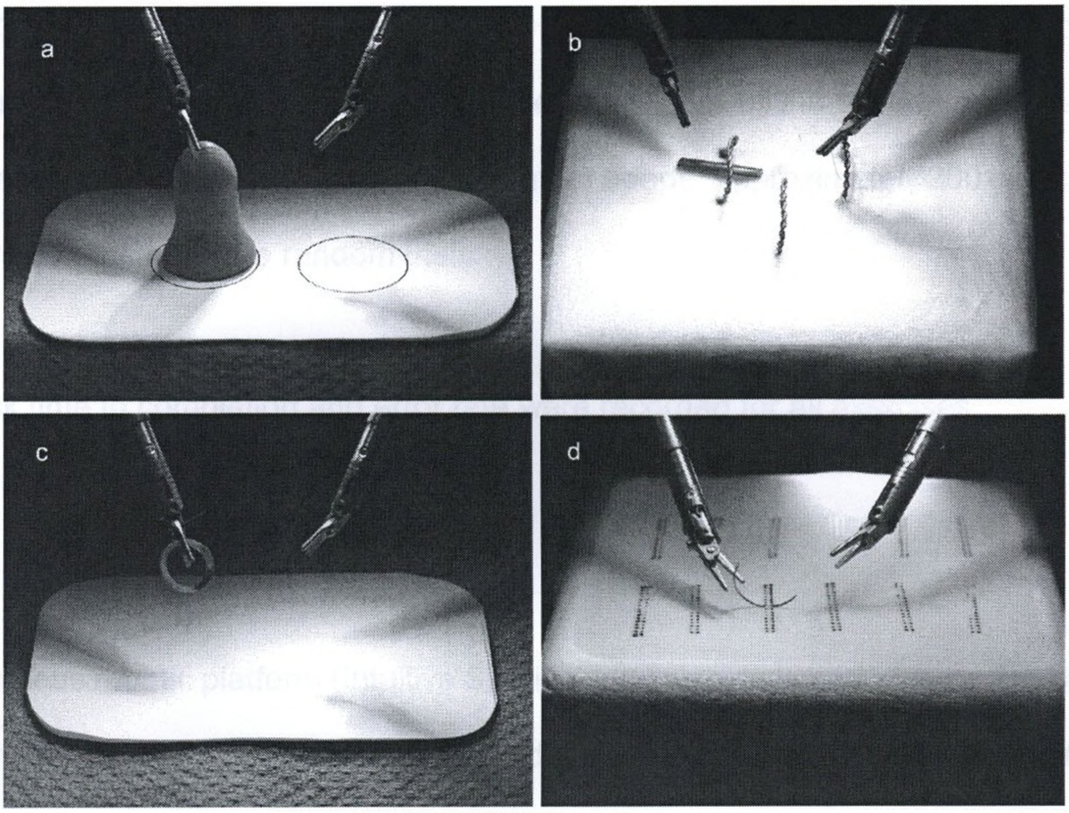

Figure 6. The four exercises (a-d) used in the experiments. These represented typical maneuvers during surgery. Predefined errors during the tasks were recorded by an observer.

Eight test subjects were assigned to complete the surgical exercises. Seven had no previous experience on the Zeus or other robotic systems. All subjects had access to the robotic system regularly. The group had a one week familiarization period, and then performed the surgical exercises at transfer latencies (T_t) from 0 to 600 msec, in increments of 100 msec. Over 1,700 exercises were conducted in the sequential trials.

Additionally, a core group of four subjects performed the exercises with random delays between 0 and 1000 msec. These subjects had been exposed to the platform five days per week over a period of approximately four months. Therefore, they continuously experienced the rigors of the system and latency demands, and had the opportunity to learn or adapt. Approximately 200 exercises were conducted in the random trials.

Task time to completion and error rate were recorded for all exercises.

2.2.2 Robotic platform

The Zeus robotic platform (Intuitive Surgical Inc.) was designed with master-slave architecture consisting of a surgeon's side console and patient side robotic arms. Each side could be connected via multiple methods including UDP Internet protocol, satellite, or communications software. Our configuration of the NetDisturb software (8) could emulate variations in latency, packet loss, or other transmission characteristics.

At the console, the surgeon sat with instrument controls in both hands and a video screen showing the surgical view directly in front (figure 7a, b). The remote surgical endoscope camera was moved left, right, up, down, etc. using a mouse control interface. Both the live surgical and operating room views were provided. The surgeon also communicated with the remote surgical team via live audio exchange using an in-room camera (Polycom Inc.).

At the patient side, three robotic instrument arms were used to perform surgery. One arm held a camera scope to provide the surgical view, while the others manipulated interchangeable instruments. The surgical arms had 5 degrees of freedom, with basic axis movements plus an additional wrist joint at the instrument end. A complete technical description of the prototype can be found in Butner and Goudoussi (3).

a

b

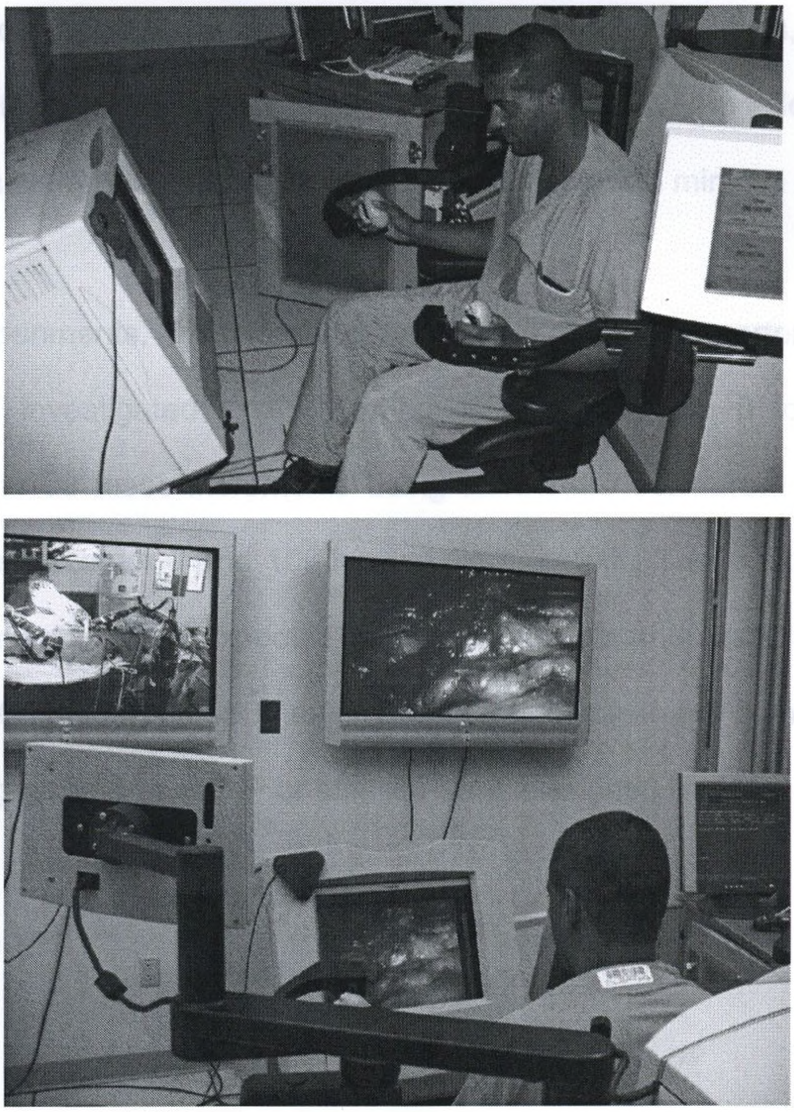

Figure 7. The robotic telesurgery laboratory set-up. The operator sits at a console (a) and has the surgical site video directly ahead on screen. Additionally, a remote room view is provided with live audiovisual connection (b).

2.2.3 Telecommunications simulation

We had access to a transcontinental internet private network (IP-VPNe), live partitioned satellite feed, and telecom simulation software. The network architecture was designed to be fully redundant with the possibility of human surgery in mind. The VPNe architecture had dual encoders, switches, and routers, and the satellite transmission could act as a back up if the VPNe failed (figure 8). Both networks were high quality, 10 Mbps connections with minimal packet loss.

For these experiments, the effects of varying latencies on performance and learning were investigated. We simulated latencies from 0 to 600 msec sequentially in 100 msec increments using NetDisturb software. Additionally, random delays between 0 and 1000 msec were tested. These latencies were chosen to simulate those expected in 'real world' communications networks. Delays from 60 to more than 500 msec are characteristic in our communications test bed during ground based IP or satellite transmissions (Table 1).

Table 1. Laboratory communications test bed

	Transmission type	*Bandwidth (Mb/sec)*	*Approximate distance roundtrip (km)*	*Latency (T_t msec)*
NetDisturb software	emulated	emulated	0	User defined
Internet protocol (private partition)	UDP/IP	10	4150	65
Satellite	Ku band	10	71000	600

2.3 Results

There were no major technical issues with the robotic platform or communications network. Overall, the system worked well and all participants were able to complete the tasks over all latencies. Participants found the exercises to be challenging, and reported some fatigue in performing the tasks at higher latencies.

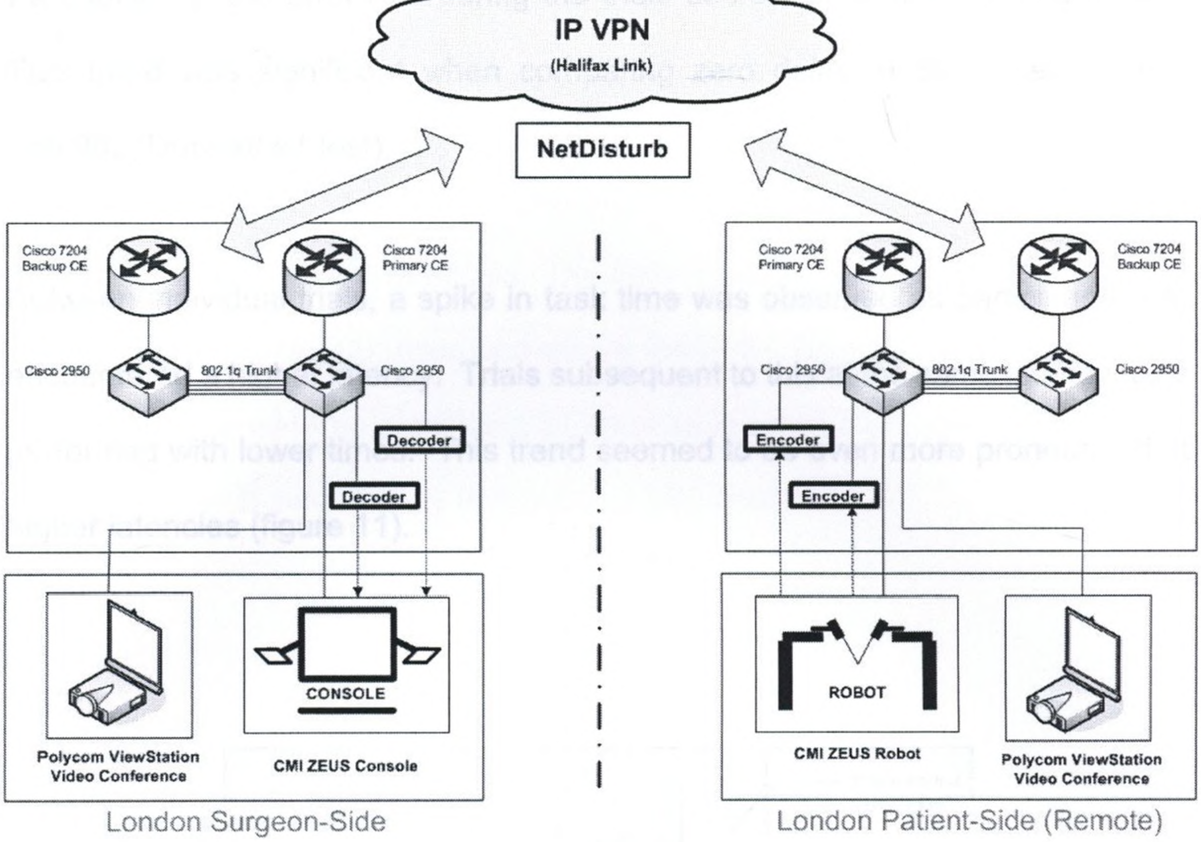

Figure 8. Communications test bed for the experiments. Signals from all devices were collected, encoded, and multiplexed by a switch (Cisco 2950), creating a single data stream directed by a router (Cisco 7204). The networking hardware was fully redundant on both sides. The system automatically chose the most reliable link. Routers on each side could be connected in different ways to emulate different modalities of deployment. These were NetDisturb software (current experiments), long-distance UDP/IP or Ku band satellite. The network was set up in conjunction with Bell Canada

2.3.1 Sequential trials

The summarized results of all exercises in the sequential trials are shown in figures 9 and 10. Task times decreased for latencies up to 300 msec, and then increased moderately. There were no significant time differences for any of the latencies compared to zero (repeated measures ANOVA overall p=0.012; Dunnett's t-test).

Paradoxically, the error rate during the trials decreased with increasing delays. This trend was significant when comparing zero delay to 500 msec (overall p=0.002; Dunnett's t-test).

Between individual trials, a spike in task time was observed as participants first encountered a higher latency. Trials subsequent to this at the same latency were performed with lower times. This trend seemed to be even more pronounced at higher latencies (figure 11).

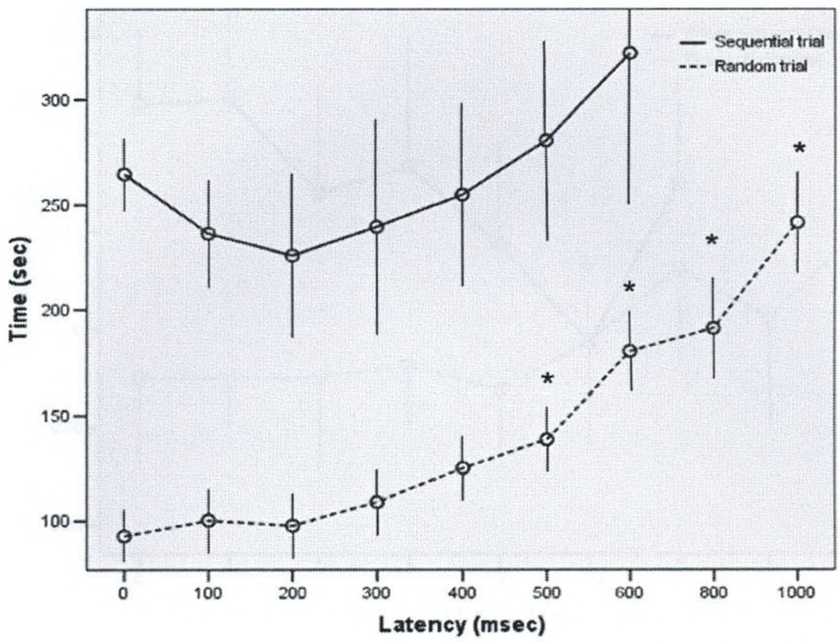

Figure 9. Overall time for task completion for the sequential and random delay trials at differing latencies. Random trial times were significantly greater compared to zero latency at 500 ms and beyond (repeated measures ANOVA, $p < 0.001$)

2.3.2 Random trials

During the random trials, participants were unaware of the latency they were to experience during an exercise. In a summary of all exercises, task times gradually increased with increasing latencies. The times were significantly higher than zero delay at latencies of 500 msec and above (p<0.001; figure 9). Despite the high latencies, there were no significant differences in error rates compared to those experienced with zero latency (overall p=0.252; figure 10).

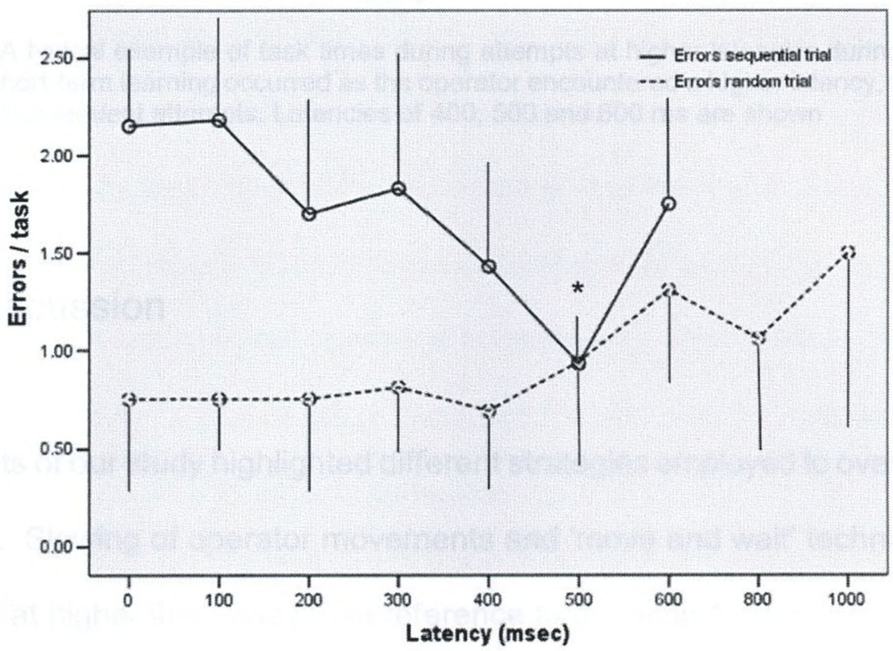

Figure 10. Error rates vs. latency for the sequential and random delay trials. There were no significant differences in error rate compared to zero latency except at 500 ms during the sequential trials (*p* = 0.002)

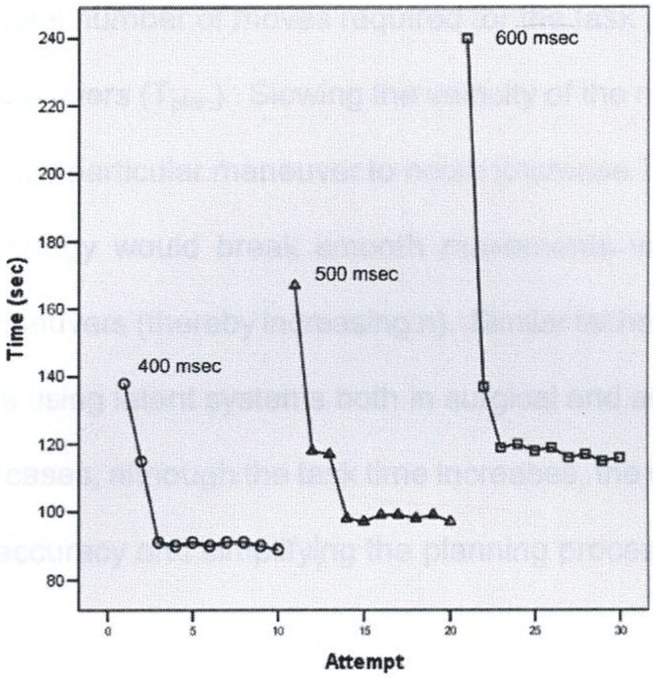

Figure 11. A typical example of task times during attempts at higher latencies during a particular exercise. Short-term learning occurred as the operator encountered a higher latency, then adapted to it during subsequent attempts. Latencies of 400, 500 and 600 ms are shown

2.4 Discussion

The results of our study highlighted different strategies employed to overcome high latencies. Slowing of operator movements and 'move and wait' techniques were observed at higher time delays. In reference to equation 1:

$$Task = \sum_{1}^{n} (T_{en} + T_t + T_r + T_{move} + T_{plan}) ,$$

the parameters under the control of the operator were the velocity of movement (T_{move}), the total number of moves required for the task (n), and the planning time between maneuvers (T_{plan}). Slowing the velocity of the movement would increase the time for any particular maneuver to occur (increase T_{move}). Employing a move and wait strategy would break smooth movements into a number of broken, staccato maneuvers (thereby increasing n). Similar techniques have been reported by operators using latent systems both in surgical and aerospace applications (9, 10). In both cases, although the task time increases, the error rate is decreased by increasing accuracy and simplifying the planning process.

The time and pressure added by recovering from an expected error, resetting instruments, and planning of a new set of maneuvers seemed to be more important for overall performance. Our test subjects worked to keep error rates low despite increasing latency (figure 10). However, whether this type of strategy could be employed within real surgical scenarios is unknown. The cadence of surgery is often predicated by clinical urgency. An operator with only the 'raw data' of latent video feedback could find urgent maneuvers quite difficult.

Both short and long term learning were observed within the experimental set. Short term learning can be seen clearly in figure 11, where the operator's time for task completion spiked with each newly encountered latency, and then decreased as accommodation occurred.

In the sequential trials, our results showed a trend of decreasing task times up to 300 msec and error rates up to 500 msec (figures 9, 10). We have associated this decrease with the effect we call long-term learning. This type of learning is associated with improving performance through repeating a task a number of times. During this period, the operators were continuously gaining experience on the system beyond the one week familiarization period. The effect of long term learning remained with the participant over the whole period of experiments (just over four months). The figures also indicate that the minimum amount of training needed to properly perform simple tasks can be achieved over relatively short periods of time, equivalent to a training period consisting of 3-4 weeks of one hour a day, three times a week.

During the random trials, a similar trend was not observed as most learning benefits had likely occurred by the four month mark. Overall task times and error rates were lower than the sequential trials, even beyond 500 msec. The participants likely demonstrated task proficiency and strategies derived from the previous four month experience. Latencies beyond 500 msec are likely to be experienced using satellite networks, and have not been previously studied (5).

2.4.1 What type of automation is appropriate for telesurgery?

Having only the raw data of latent video feedback in a real surgical scenario could be quite difficult for the operator. Unstable patients or challenging tissue manipulation would be incongruent with slowing of movements to overcome latency. Additionally, the duration of surgery could introduce significant fatigue for the operator. The question of user predictive or other automation for use in telesurgery should be addressed.

In predictive displays, the operator is shown what will be expected to happen over the next interval of time, given the current system inputs. The prediction is usually shown on the operator's screen. This type of technology has been used on pilot's displays, ships and submarines, and air traffic control displays for several years. In robotic telesurgery, a predictive display would show the surgeon where instruments would end up given their current input and the latency. The surgeon could then 'lead' the actual process and perform larger maneuvers with confidence.

For operator delays greater than 300 msec, Held et al. (11) has shown that sensory motor adaptation is impossible, and that subjects dissociate their own hand movements from those of the telerobot at these delays. The simplest predictive displays would show the operator a computer generated screen cursor which is extrapolated forward in time. Given the current conditions of the system, a predictive model can be run many times faster than the actual process (figure 12). An expected final point is shown if 'all conditions are kept the same as present,' and could indicate where tools will stop with the given latency. Even these simple displays improve the performance of the operator (12). More sophisticated predictive technology could provide a virtual representation of the robot and its environment. In any movement, the virtual display can be used to understand how the robot will react given the current network (13, 14). Leading the actual process and performing larger maneuvers can decrease task time by as much as 50% (15).

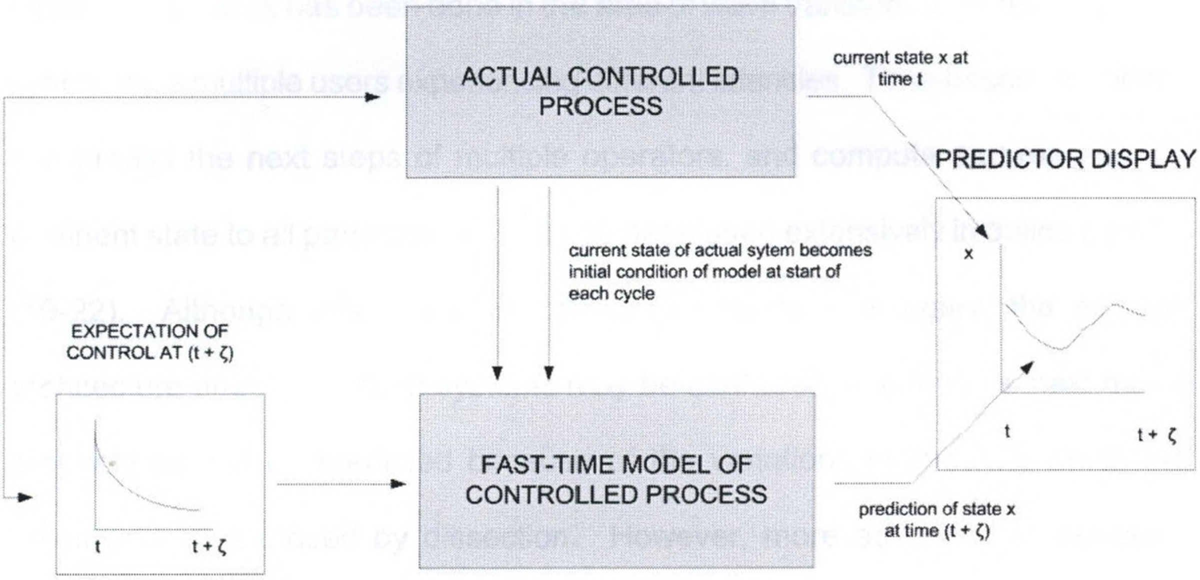

Figure 12. The Ziebolz and Paynter technique for latent systems prediction. The predictor model is run many times faster than the actual operating process. Therefore, prediction is based on the current inputs of the operator and constantly updated for accuracy

Whether higher levels of command are appropriate for telesurgery is unknown. In supervisory control, the operator commands the robot to perform a set of maneuvers, and monitors how they are performed. By doing so, the operator is removed from the control loop. The robot would need to possess sensory or other analytical capability in order to carry out the instruction set. This could be quite difficult in a three dimensional space with variations in tissue elasticity and homogeneity. Current robots can perform complex, autonomous tasks in predictable, 'object stable' environments (16-18). However, even the best visual and force sensing available would probably not suffice for autonomous tissue dissection or manipulation.

Finally, much work has been done in the area of wave transformation techniques to synchronize multiple users experiencing different latencies. Time-based algorithms can predict the next steps of multiple operators, and compute and represent a pertinent state to all participants. This has been used extensively in online gaming (19-22). Although this is not directly applicable to telesurgery, the network architecture underlying such systems may be useful. The surgeon's 'next move' probably cannot be predicted because of the variations in anatomy which are unknown until exposed by dissection. However, more advanced server-client architectures interposed between operator and slave surgical robots may help minimize the effects of long latencies.

In conclusion, we have shown that operators are capable of performing surgical exercises at significant transmission delays. The surgical platform studied has been used effectively for small latencies (300 msec or less). For delays greater than 500 msec, slowing of movements minimized errors and simplified task planning. However, such strategies are not optimal for the cadence of surgery. Further platform modifications, such as visual or virtual reality cues, are required to provide the operator with more reliable predictors during high latencies.

References

[1] Fabrizio M, Lee B, Chan D, et al. Effect of time delay on surgical performance during telesurgical manipulation. J Endourol 2000; 14(2): 133-138.

[2] Sheridan T. Teleoperation, telerobotics and telepresence: A progress report. Control Eng Practice 1995;3(2): 205-214.

[3] Butner S, Ghodoussi M. Transforming a Surgical Robot for Human Telesurgery. IEEE Trans Robot Autom 2003;19(5): 818-824.

[4] Marescaux J, Leroy J, Gagner M, et al. Transatlantic robot-assisted telesurgery. Nature 2001; 413: 379-380.

[5] Anvari M, Broderick T, Stein H, et al. The impact of latency on surgical precision and task completion during robotic-assisted remote telepresence surgery. Comput Aid Surg 2005; 10(2): 93-99.

[6] Chong N, Kotoku T, Kohtaro O, et al. Remote coordinated controls in multiple robot cooperation. Proc IEEE Int Conf Robot Autom 2000: 3138-3143.

[7] Thompson J, Ottensmeyer M, Sheridan T. Human factors in tele-inspection and tele-surgery: Cooperative manipulation under asynchronous video and control feedback. MICCAI 1998: 368-376.

[8] ZTI-Telecom NetDisturb. www.zti-telecom.com/fr/pages/netdisturb.htm

[9] Ferrell W. Remote manipulation with transmission delay. IEEE Trans Human Factors in Electron 1965: HFE 6, no1.

[10] Kim T, Zimmerman P, Wade M, Weiss C. The effect of delay visual feedback on telerobotic surgery. Surg Endosc 2005;19: 683–686.

[11] Held R and Durlach N. Telepresence, time delay, and adaptation. In: S. R. Ellis, Ed., Pictorial Communication in Virtual and Real Environments. Taylor and Francis, 1991, pp. 232-246.

[12] Bejczy A and Kim W. Predictive displays and shared compliance control for time-delayed manipulation. Proc IEEE Int Workshop Intelligent Robots Syst IROS 1990; 407-412.

[13] Lane J, Carignan C, Akin D. Advanced Operator Interface Design for Complex Space Telerobots. Autonomous Robots 2001;11: 49–58.

[14] Sayers C, Paul R. Coping with Delays: Controlling Robot Manipulators Underwater. Industrial Robot 1994 21(5): 24-26.

[15] Sheridan T. Space Teleoperation Through Time Delay: Review and Prognosis. IEEE Trans Robot Automat 1993;9(5): 592-606.

[16] DeSouza G, Kak A. A Subsumptive, Hierarchical, and Distributed Vision-Based Architecture for Smart Robotics. IEEE Trans Sys Man Cyber 2004;34(5):1988-2002.

[17] Galbraith J, Kenyon G, Ziolkowski R. Time-to-Collision Estimation from Motion Based on Primate Visual Processing. IEEE Trans Pat Anal Mach Intellig 2005;27(8): 1279-1291.

[18] Kondo N, Monta M, Fujiura T. Fruit harvesting robots in Japan. Adv Space R 1996;18(1): 181-184.

[19] Arcara P, Melchiorri C. Control schemes for teleoperation with time delay: A comparative study. Robotics Autonom Sys 2002;38: 49–64.

[20] Cronin E, Kurc A, Filstrup B, Jamin S. An efficient synchronization mechanism for mirrored game architectures. TSS.tex 2003;15(18): 1-30.

[21] Feretti S. Interactive maintenance for event synchronization in massive multiplayer online games. Technical report UBLSC 2005-05: 1-202.

[22] Munir S, Book W. Internet-Based Teleoperation Using Wave Variables With Prediction. IEEE/ASME Trans Mechatronics 2002;7(2): 124-133.

Chapter 3

Emulation and evaluation of basic clinical procedures

Real surgery involves more complex movements and tissue interaction, and often requires increased cadence.

This set of experiments was designed to test telesurgery in live animals by emulating basic clinical procedures. The experiments were designed to show whether the operator is capable of the increased demand imposed by such procedures. Additionally, the behavior and reliability of ground and satellite based communications was assessed

A version of this chapter has been published in The International Journal of Medical Robotics and Computer Assisted Surgery entitled:

"Robotic telesurgery: a real-world comparison of ground- and satellite-based Internet performance" by R Rayman, K Croome, N Galbraith, R McClure, R Morady, S Peterson, S Smith, V Subotic, A Van Wynsberghe, R Patel and S Primak.

3.1 Introduction

Robotic technology is continuing to expand minimally invasive surgery (1). With a robotic system, the surgeon is able to control multiple instruments from a console while viewing a three-dimensional (3D) image of the surgical site. These systems have a master–slave architecture, with the surgeon displaced from the patient in a non-sterile area. The surgeon sees the operative site and controls the robotic instruments from the console, thereby closing the control loop. The usual displacement between surgeon and patient is 5–10 m. However, extending master–slave control may introduce powerful, new capabilities.

Telesurgery is defined as the performance of robotic surgery over long distances with a communication link. This new area holds promise for efficient and cost-effective services. Telesurgery has the potential to extend surgical expertise, collaboration and training, provide remote community care and save transportation costs.

Although teleoperation has been studied extensively during the past 20 years (2), the field of telesurgery is quite new. The first proof of concept was performed by Marescaux *et al.* (3) in 2001. Since then, Anvari *et al.* (4) set up a telesurgery service spanning 400 km within Canada. This service successfully treated 21 patients in a variety of procedures. Despite these powerful examples, studies of performance during telesurgery are not well developed. Delays between operator input and instrument reaction can be significant over long distances. During Strasbourg-to-Paris animal experiments, Butner and Ghodoussi (5) proposed 330 ms communications latency as a comfort zone for surgeons. In dry laboratory studies, significant increases in task completion times occurred when users experienced delays of 500 ms and beyond (6, 7). Recently, Hanley *et al.* (8) reported on a da Vinci® telesurgery system, in which swine nephrectomies were performed, with latencies in the range 550–980 ms. The surgeons felt that such latencies were feasible for performing telesurgery, and further data should be published soon by this group.

Investigations to date have employed only ground-based Internet protocol (IP) networks to connect master to slave sites. However, in cases of remote communities, ground-based IP may be insufficient or unavailable. Additionally, if ground-based IP were available, satellite remains a flexible and mobile back-up in case of communications failure. Finally, maintaining high bandwidth ground IP may be cost-prohibitive.

We chose a pig animal model to compare ground-based performance directly to satellite and to characterize the effects of satellite bandwidth on performance. We hypothesized that telesurgery would be possible during these emulated clinical procedures. However, satellite-based telesurgery could be impractical because signal delays were approximately 10 times greater than land-based, and exceeded 500 ms. Finally, satellite-based telesurgery would not be possible beyond a lower limit bandwidth.

3.2 Materials and methods

3.2.1 Telecommunications network

The telecommunications test bed was set up in conjunction with industrial partners. In all experiments, a bandwidth of 10 Mb/s was provided by either ground or satellite. The ground network was redundant and partitioned and spanned a round trip from London, Ontario, to Halifax, Nova Scotia (ca. 4000 km). The transmission time was approximately 55 ms. Including high-speed encoding, the total latency for the operator was approximately 200 ms.

The satellite network was again privately partitioned, with 10 Mb/s bandwidth. The routing was round-trip from London to Toronto and then to a telecommunications satellite operating in the Ku band (12–14 GHz). The transmission time was approximately 600 ms. Test bed characteristics and configuration are shown in Table 2 and Figure 13. A protocol of switching between the ground and satellite loops was agreed upon with the industrial partners, and switching was routinely used during the actual experimentation.

Table 2. Laboratory communications test bed

	Transmission type	*Bandwidth (Mb/sec)*	*Approximate distance roundtrip (km)*	*Latency (T_t msec)*
NetDisturb software	emulated	emulated	0	User defined
Internet protocol (private partition)	UDP/IP	10	4150	65
Satellite	Ku band	10	71000	600

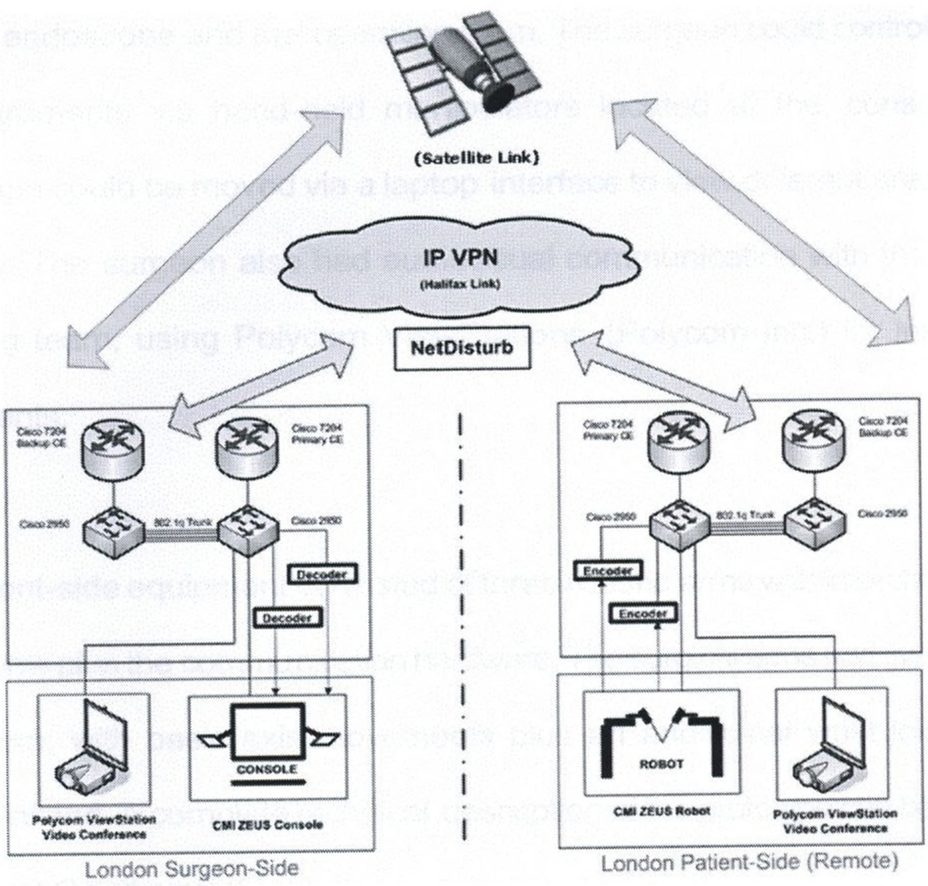

Figure 13. Communications test network used in the study. Both ground and satellite Internet protocol connections were redundant and privately partitioned

3.2.2 Robotic platform

The Zeus® telesurgery prototype (Intuitive Surgical Inc.) has been used and described by our laboratory in previous studies (6,9). The prototype consisted of surgeon-side and patient-side telesurgery equipment in a master–slave architecture. The equipment was located in adjacent rooms but with no direct communication or line of sight between the two.

On the surgeon-side, full audiovisual capability was supplied from both the surgical endoscope and the operating room. The surgeon could control patient-side instruments via hand-held manipulators located at the console. The endoscope could be moved via a laptop interface to view different areas within the body. The surgeon also had audiovisual communication with the remote operating team, using Polycom ViewStations (Polycom Inc.) for instrument adjustments.

The patient-side equipment consisted of three robotic arms with interchangeable instruments plus the communication hardware. The surgical arms had five degrees of freedom, with basic axis movements plus an additional wrist joint at the instrument end. A complete technical description of the prototype can be found in Butner and Goudoussi (5).

For these experiments, the operator was familiar with the Zeus telesurgery platform and had recently worked with it. Additionally, the operator had frequently performed a left internal mammary artery (LIMA) dissection by both conventional and robotic methods.

3.2.3 Animal study: comparing ground to satellite performance

A total of 15 pigs were used in the two phases of experiments described here. In eight pigs, LIMA dissection was conducted to compare ground to satellite-based telesurgery. These animals weighed 40–50 kg.

The pigs were sedated using an intramuscular injection of 150 mg tiletamine hydrochloride mixed with 400 mg xylazine hydrochloride and 0.04 mg/kg atropine. The animals were intubated and general anaesthesia was maintained, using a 50: 50 mixture of nitrous oxide: oxygen and isoflorane in the range 1.75–2.25%.

The femoral artery was cannulated percutaneously to provide systemic blood pressure monitoring. The femoral vein was similarly accessed for fluid administration, and was connected to a slow normal saline drip.

All experiments were conducted with trained animal technicians and had been previously approved by our University Ethics Committee.

Following general anaesthesia, a midline sternotomy was performed and the left hemithorax retracted using a surgical IMA retractor (a sternotomy was necessary to provide working room, to simulate a closed chest hum an IMA dissection). The ports for the robotic camera and instrument arms were introduced into the right chest wall. A 5 mm, 30° endoscope (Karl Storz Inc.) was used for the camera port. The right robot arm held an ultrasonic dissector (Harmonic scalpel, Ethicon Endosurgery Inc.) and the left hand grasping forceps.

LIMA dissection was conducted using the network. Within the same animal experiment, the surgery was conducted for 30 min with the ground IP and then switched for 30 min on satellite IP. The switchover from ground to satellite was performed by our industrial partners and took 1–2 min.

The length of vessel dissected was recorded for each portion of the experiment. Additionally, an observer group (n = 5) scored the quality of surgery, based on a global rating scale as seen in Table 3. This scale has been previously validated, and items on the scale have been developed to be procedure-independent (10). We adapted the scale by excluding three criteria that were not applicable and adding one criterion (Control of bleeding) using a similar scoring rationale. The observer group was familiar with the Zeus platform and had previously operated it in dry laboratory studies. The group was allowed complete access to the patient- and surgeon-side operating areas in order to form criteria scores. LIMA patency was checked at the end of the experiment by transecting the vessel and ensuring that brisk bleeding was present and that the vessel had not been damaged. The animals were sacrificed at the end of the experiment by intravenous euthanyl infusion.

3.2.4 Animal study: effects of satellite bandwidth

In seven pigs, LIMA dissection was conducted via satellite as the sole means for communication. Telesurgery performance was recorded as satellite bandwidth was sequentially decreased. All experiments were conducted with trained animal technicians and had been previously approved by our University Ethics Committee. Anaesthetic induction and maintenance were performed in a similar fashion to the previous experiments. The set-up of the robot and instruments were also similar.

During each animal experiment, satellite and encoder bandwidth were sequentially decreased in 10 min intervals as LIMA dissection was performed. During each interval, an observer group scored the quality of surgery, using a global rating scale (Table 3). The bandwidth at which surgery was no longer possible was determined by the operator and the observer group. The animals were euthanized at the end of each experiment.

TABLE 3.

GLOBAL RATING SCALE OF OPERATIVE PERFORMANCE

Please circle the number corresponding to performance in each category

Respect for tissue:

1	2	3	4	5
Frequently used unnecessary force on tissue or caused damage by inappropriate use of instruments		Careful handling of tissue but occasionally caused inadvertent damage		Consistently handled tissues appropriately with minimal damage

Time and motion:

1	2	3	4	5
Many unnecessary moves		Efficient time / motion but some unnecessary moves		Clear economy of movement and maximum efficiency

Instrument handling:

1	2	3	4	5
Repeatedly makes tentative or awkward moves with instruments by inappropriate use of instruments		Competent use of instruments but occasionally appeared stiff or awkward		Fluid moves with instruments and no awkwardness

Flow of operation:

1	2	3	4	5
Frequently stopped operation and seemed unsure of next move		Demonstrated some forward planning with reasonable progression of procedure		Obviously planned course of operation with effortless flow from one move to the next

Control of bleeding:

1	2	3	4	5
Major bleeding causing procedural stoppage and repair efforts		Minor bleeding with most sites coagulated or ligated		Little to no bleeding and good hemostasis at end of procedure

3.3 Results

3.3.1 Comparing ground to satellite performance

The communications network in these experiments performed well. There were no instances of blocked or dropped communications, and the switchover from ground to satellite IP was smooth and quick. Once our industrial partners were requested, they reacted within 1–2 min, and the picture switch was close to instantaneous.

During the ground portion, the audiovisual communications were of high quality. The surgical endoscope picture was clear, with no pixilation observed. Upon switchover to satellite, the picture was still clear, with minor pixilation occurring every 5–10 min. There was a perceivable difference in latency, but this could be quickly accommodated by the operator.

The LIMA length taken down for each portion of the experiment is shown in Figure 14. There was no significant difference between ground- and satellite-based telesurgery in this exercise (paired t-test; $p > 0.05$). Also, there were no significant differences in the quality of surgery based on the global rating scale (Figure 15). The LIMA was patent and briskly bled at the end of each experiment, with no damage to the artery observed.

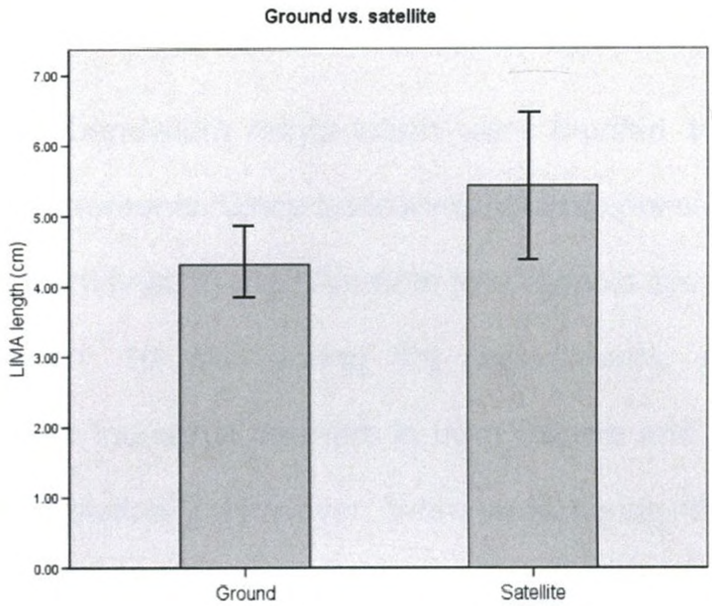

Figure 14. There was no significant difference between left internal mammary artery (LIMA) length dissected using ground vs. satellite-based connections ($p > 0.05$). The latency of satellite transmission was >10-fold that of ground (ca. 600 vs. 55 ms)

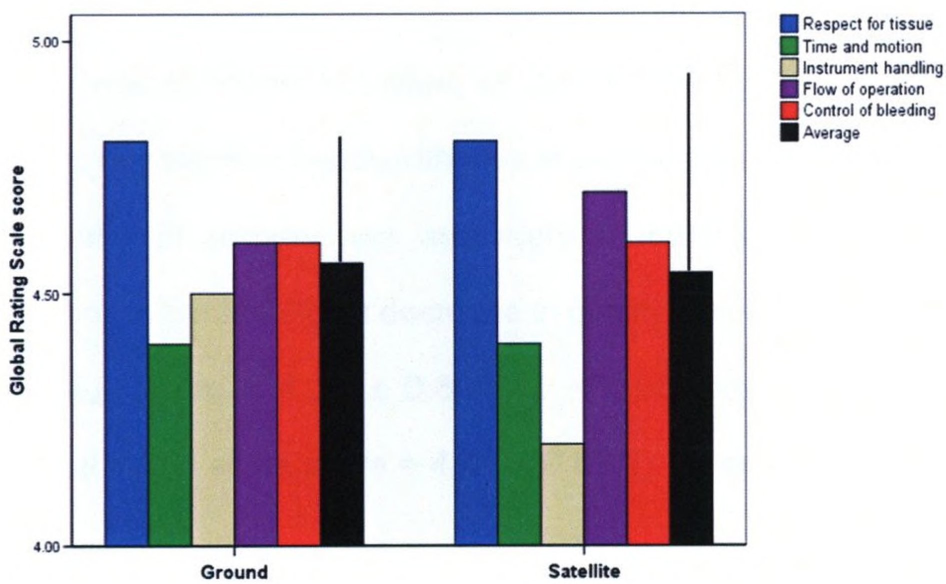

Figure 15. There was no significant difference between Global rating scale scores comparing ground or satellite modalities, either between pairs or on average ($p > 0.05$; error bars shown for averages only)

3.3.2 Effects of satellite bandwidth

The effects of bandwidth degradation were studied to identify minimum acceptable requirements. Since bandwidth is an expensive resource, it was important to identify such requirements for practical systems. To decrease bandwidth every 10 min during the experiments, our London team coordinated with industrial partners in both Ottawa and Toronto. This was more difficult logistically. However, there were no significant delays in the switching process. The image switchover to a lower bandwidth occurred nearly instantaneously. There was noticeable pixilation at bandwidths below ca. 5 Mb/s. Picture locking occurred in some instances.

The combinations of satellite and encoder bandwidths during the LIMA dissection are shown in Figure 16. The '■' symbols represent combinations in which surgery was no longer possible, as determined by the operator and observer team. For satellite bandwidth, this lower level was approximately 4 Mb/s. The quality of surgery was adversely affected as bandwidth was degraded. There was a significant decrease in quality of surgery at bandwidth 3 Mb/s (average score = 4.10 ± 0.80/5; $p < 0.05$) compared to 9 Mb/s (average global rating scale score = 4.38 ± 0.66/5), as seen in Figure 17.

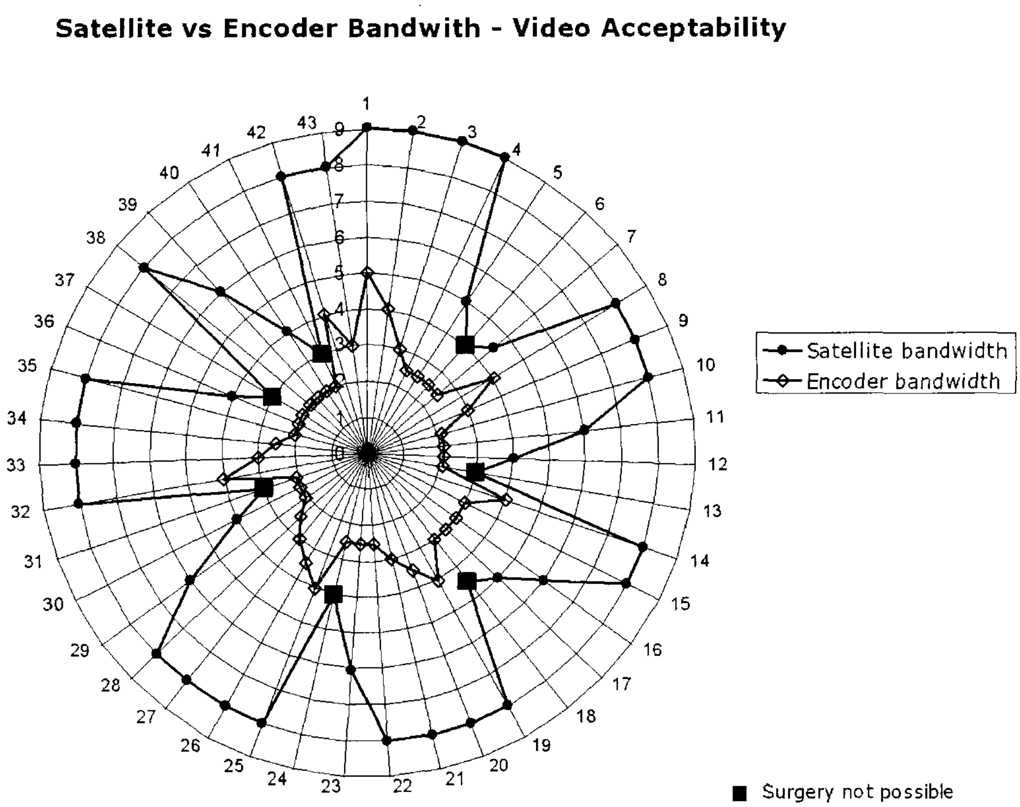

Figure 16. Satellite and encoder bandwidths were sequentially decreased to identify a minimum level for telesurgery. The bandwidth 'pipe' is shown as concentric circles (9–0 Mb/s). Changes in bandwidth combinations using 7 pigs are seen radially moving clockwise from spoke 1 in the 43 spokes. ■, satellite bandwidths at which surgery was no longer possible (ca. 4 Mb/s)

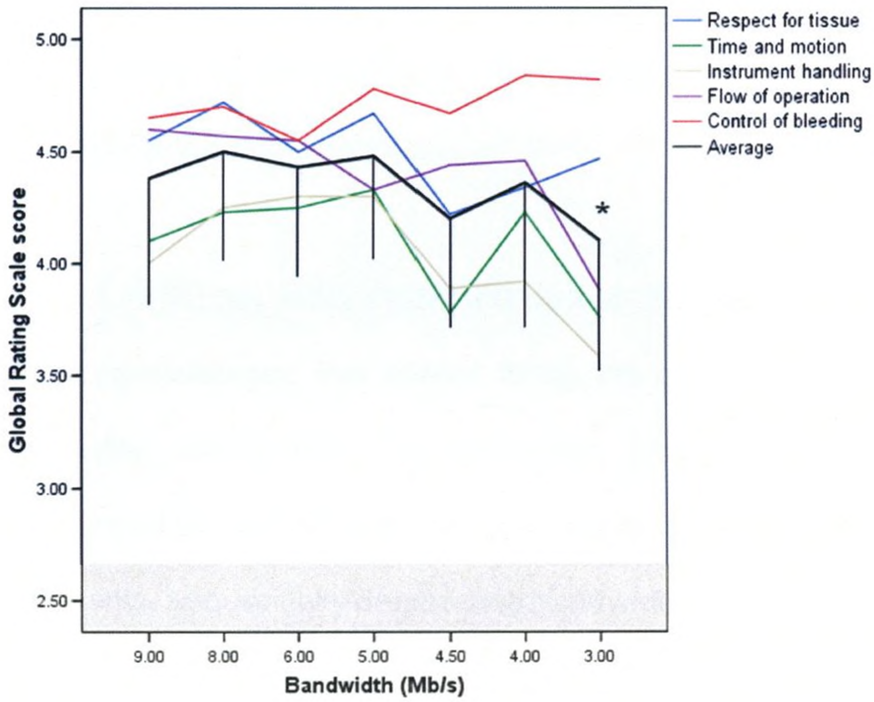

Figure 17. Global rating scale scores had a decreasing trend as satellite bandwidth was decreased. There was a significant decrease in the average score at 9 Mb/s (4.38 ± 0.66) compared to 3 Mb/s (4.10 ± 0.80; $p < 0.05$). Error bars are shown only for overall mean scores

3.4 Discussion

These experiments demonstrated that satellite communication may be effective for telesurgery. The latency for satellite-based IP was more than double that of ground- based IP. However, surgical results were not different between the two. The length of LIMA dissected and the quality of surgery were not significantly different by switching modalities. Notably, satellite-based IP may be considered as an alternative or back-up means if ground-based IP fails or is unavailable. Satellite-based IP could also be used as a single source of communication; however, the operator must be aware of longer delays and should have redundant satellite access available.

The protocols of switching were restricted by our industrial partners. In the ground–satellite comparison, this meant fixing the order of switching from ground to satellite, rather than randomization. However, this order still simulated a failure of ground-based IP and a switch to satellite back-up. In the satellite experiments, sequentially decreasing bandwidth made finding a 'point of failure' more definitive.

We were interested in defining a lower limit to satellite bandwidth. The costs of satellite bandwidth are high, and users should be aware of what minima are required. Our experiments defined approximately 4 Mb/s as a level at which telesurgery could no longer be conducted. An appropriate 'buffer' in order to maintain a comfortable picture quality would likely be around 6 Mb/s. Hanley *et al.* (8) have correctly pointed out that cost is critical in ground-based telesurgery, and satellite bandwidth is even more expensive. Although the private bandwidth for our experiments was contributed by TeleSat Canada, maintaining this by purchasing it privately could cost more than $100 000/month

(11). Such access would need to be used nearly continuously by health care providers to be cost-effective.

Despite these results, the latencies imposed by satellite communications were perceivable and required constant compensation by the operator. There was no automation in our system to correct for this. Degradations due to satellite latency were of several types. First, movement-to-view delays occurred as the operator commanded an instrument motion, which was not seen at the console until approximately 500 ms later. A staccato 'move and wait' strategy with smaller instrument displacements was employed to counteract this. Second, minor pixilation occurred, which impaired video interpretation. By waiting for the next clear frame, the operator was able to continue with the surgical task. Finally, double-handed manipulations with high latencies needed to be done in a slow, deliberate manner to minimize errors.

In cases with complications, the operator may experience further pressure and adaptation could be degraded. Trying to rush or 'beat the clock' may only compound errors. Notably, McKenzie and Ware (12) have shown that latency has a multiplicative (not additive) effect on degrading performance. The use of predictive or virtual reality methods to overcome latencies >500 ms needs to be explored (6,13).

A manual switchover from ground to satellite communi cations and between satellite bandwidths was conducted in our experiments. In practice, redundancies should be automated in order to detect a primary failure and switchover to back-up communications. If satellite were used primarily, then bandwidth adjustments could be made 'on the fly' to provide effective resource utilization.

Whether telesurgery becomes a reality in North American or European health care remains to be seen. McLean (14) has studied the legal and ethical considerations for making this happen. There is inherent sense in allowing special experts to more easily disseminate knowledge and skill to patients. In reality, this would likely begin as intraoperative teleconsul tation and then progress to telesurgery. Legal and licensing issues should be designed for this. Patients could then appreciate the benefit of multiple experts for their care.

References

[1] *Intuitive Surgical: The Robotics Revolution is Real.* Cowen and Co., 2006; www.cowen.com/ResearchCoverage.

[2] Sheridan T. Space teleoperation through time delay: review and prognosis. IEEE Trans RobotAutomat 1993; 9(5): 592–606.

[3] Marescaux J, Leroy J, Gagner M, *et al.* Transatlantic robot- assisted telesurgery. Nature 2001; 413: 379–380.

[4] Anvari M, McKinley C, Stein H. Establishment of the world's first telerobotic remote surgical service. Ann Surg 2005; 241(3): 460–464.

[5] Butner S, Ghodoussi M. Transforming a surgical robot for human telesurgery. IEEE Trans RobotAutom 2003; 19(5): 818–824.

[6] Rayman R, Croome K, Galbraith N, *et al.* Long-distance robotic telesurgery: a feasibility study for care in remote environments. Int J Med Robotics Comput Assist Surg 2006; 2: 216–224.

[7] Anvari M, Broderick T, Stein H, *et al.* The impact of latency on surgical

precision and task completion during robotic-assisted remote telepresence surgery. Comput Aided Surg 2005; 10(2): 93–99.

[8] Hanley E, Miller B, Herman B, *et al.* Remote stereoscopic surgery using the public Internet. European Association of Endoscopic Surgeons Congress, Berlin, Germany, 2006.

[9] Rayman R, Primak S, Patel R, *et al.* Effects of latency on telesurgery: an experimental study. Med Imag Computing Comput Assist Intervent 2005; 8:57–64.

[10] Reznick R, Regehr G, MacRae H, *et al.* Testing technical skill via an innovative 'bench station' examination. Am J Surg 1997; 173: 226–230.

[11] Satellite Signals (homepage). Satellite Signals Ltd, c. 1999–2006. Internet vsat access via satellite: costs: http://www.satsig.net/ivsatcos.htm.

[12] MacKenzie I, Ware C. Lag as a determinant of human performance in interactive systems. Interchi 1993; 488–493.

[13] Bejczy A, Kim W. Predictive displays and shared compliance control for time-delayed manipulation. Proceedings of the IEEE International

Workshop on Intelligent Robot Systems (IROS), Ibaraki, Japan, 1990; 407–412.

[14] McLean T. The legal and economic forces that will shape the international market for cybersurgery. Int J Med Robotics Comput Assist Surg 2006; 2: 293–298.

Chapter 4

Investigation of learning and training for telesurgery

Telesurgery is a new method of performing robotic surgery. Therefore, the training of surgeons on such systems may differ from traditional methods. A break down of surgery into basic tasks at sequentially increasing or full latency may show which method of training is more effective. A comparison for training in telesurgery may then be made.

4.1 Introduction

Telesurgery is defined as the performance of robotic surgery over a distance using a communication link. Telesurgery extends a surgeon's reach, and can provide a cost effective way for experts to operate on remote patients. Such communications may increase training and collaboration between surgeons, reduce transportation costs, and bolster impoverished communities.

Telesurgery is likely to expand over the next five to ten years. However, the promise of telesurgery also introduces problems. Delays within a telesurgical system can be 500 ms or more (1). The operator must cope with such delays. Currently, there are no predictive or other tools available to compensate for this. The training of operators for telesurgery will be critical.

The issue of remote teleoperation has been widely studied in non medical areas (2-5). Compensations for latency have been divided into three broad categories. In predictive control, predictive approaches provide a model for the remote slave system to compensate for the delay. Bilateral control provides for dual input from the master (force input to velocity output), and dual reaction from the slave (velocity input to force output). Finally, teleprogramming allows supervisory control to the operator and some local autonomy to the slave. Virtual reality (VR) techniques fit into this category (4).

The feasibility of long distance telesurgery was demonstrated by performing a trans Atlantic surgical procedure on a patient with a prototype system (6). Subsequently, an interim telesurgical service from southwestern to northern Ontario, Canada was set up in which 21 patients were treated (7). In both cases, the operator dealt with the 'raw data' of the telesurgery video source. In order to do so, operators slow down, or employ a 'move and wait' strategy to avoid past pointing or other errors (8).

Methods of training and learning for telesurgery have not been yet investigated. A training study for telesurgery is critical. The present study aims to evaluate training for telesurgery by breaking surgery down into typical basic maneuvers. Subsequently, we propose to identify differences in training proficiency by comparing groups training with sequentially increasing latency versus full latency. A public Internet connection is used to illustrate that such training may occur using a low cost, accessible method.

We hypothesize that the training of subjects using a telesurgery simulator could show which methods of training are more effective, and that trainees experiencing full latency (700 ms) throughout all exercises would perform better than those training at zero latency and then adapting to the delay.

4.2 Materials and methods

4.2.1 Experimental set up

A low cost, real world solution was sought to provide communications for the exercises. The local area network (LAN) at The University of Western Ontario was used as a telecommunications test bed. This provided a realistic, variable traffic network. Latency was simulated using commercially available software (Shunra VE Desktop, Shunra Software Ltd, Philadelphia, PA), which allowed a wide range of delays, packet losses and other parameters to be simulated. For this investigation, we chose to study 0, 350, and 700 ms delay.

The test exercises were displayed on a laptop with a commercially available web camera (Logitech Quickcam, Fremont, CA), and a recording and receiving laptop were connected (Skype Technologies S.A., Luxembourg, EU). The telecommunications setup is shown in figure 18.

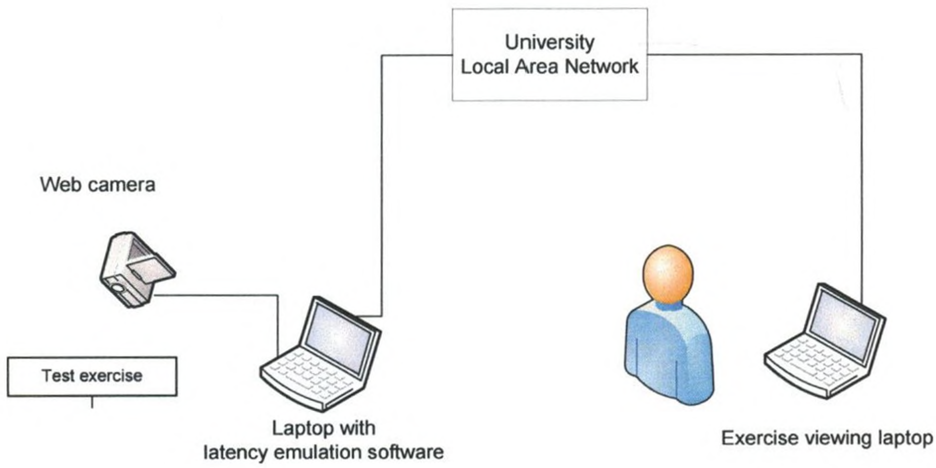

Figure 18. The setup for the latency exercises. A web camera provided the picture of the exercise to be done. This picture was sent over the University local area network. Additional latency could be added using commercially available software. The subject viewed the exercise on a viewing laptop with their hands blinded. This was done for all trials except zero latency, in which direct viewing was allowed.

4.2.2 Test exercises

The test exercises had been previously established in other studies (9 - 12). We chose exercises which would test motor dexterity, and also mimic typical surgical maneuvers. The Purdue pegboard test involved putting as many pegs as possible sequentially into a vertical row within a 30 s period. The hole steadiness test and straight path test showed the ability to hold a point object steadily in space, and the ability to perform a simulated straight cut in surgery respectively (figure 19a, b, c).

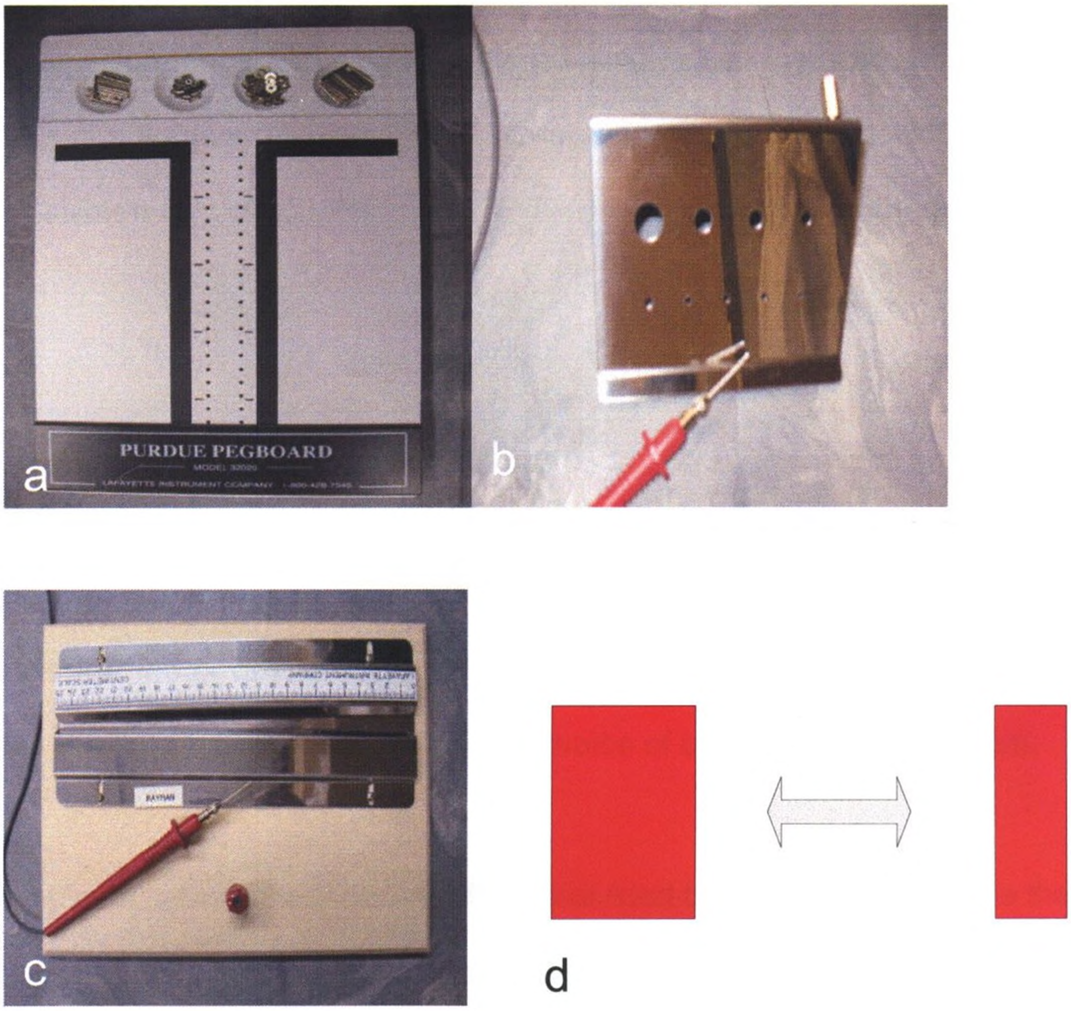

Figure 19. The four test exercises. The Purdue pegboard exercise (a) showed how many pegs could be placed by the subject with their dominant hand in a 30 s period. The hole steadiness exercise (b) tested grasp steadiness within holes of decreasing size. The straight line cut exercise (c) showed how well subject could trace a straight line without touching the borders of a narrowing groove. The Fitts' law exercise (d) tested target pointing between rectangles of varying width and distance.

A basic Fitts' law exercise was used to demonstrate performance changes with latency (figure 19d). The software program for this was developed by one of the coauthors within our lab (Almond, unpublished). Fitts' law is a mainstay of human performance research, and is derived from information theory (13). It can be used to measure performance with simple target pointing tasks. Fitts showed that the movements of a subject pointing within rectangle targets of varying width W and distance between targets D could be quantified using information theory by the expression:

$$ID = \log_2\left(\frac{D}{W} + 1\right)$$

where ID is the Index of Difficulty. Note that the term ID has no units, and is expressed in the unit 'bits' secondary to the choice of base 2 for the logarithm.

When completing a task, the Index of Difficulty divided by the time to complete the movement (MT) will give a representation of the rate of task completion in bits / s. This is also known as the Index of Performance (IP) and can be thought of broadly as the 'bandwidth' of the subject while doing the task:

$$IP = \frac{ID}{MT}$$

Rearranging and allowing for a non zero intercept 'a' of the subject, sometimes thought of as reaction time, gives:

$$MT = a + b \cdot ID$$

where here a plot of Movement Time versus Index of Difficulty should give a straight line plot with the inverse of the slope 1/b representing the Index of Performance.

In this case, Fitts' law was used to compare the performance of operators experiencing sequential increases in latency (0, 350, 700 ms) to those experiencing full latency only (700 ms). As subjects performed the Fitts' law exercise, the appropriate delay between mouse movement and cursor on screen reaction was applied. Time for task completion, distance between targets, and target width were automatically varied by the program. Each subject did ten repetitions of varying D versus W combinations during one trial.

Fitts' law applies well to an operator on a telesurgery platform for simple tasks. During robotic surgery, the operator is constantly required to identify, locate, and manipulate new tissue locations. This 'target exercise' is analogous to the target pointing model set up here. In both cases, the operator must move back and forth between specific locations. Additional, both require the operator to interact within a human computer interface (HCI).

4.2.3 Experimental groups and analysis

Eight subjects from our lab were asked to perform the exercises. The subjects were given preset general instructions and instructions on how to do the exercises, and were allowed one practice session before beginning. Subjects were randomly assigned to do two exercise types with delays increasing sequentially in three steps (0; 350; 700 ms). Three repetitions of the exercise were done at each latency. The other two exercise types were done with full latency (700ms) at the outset. Three sets of three exercises (total nine) were done with full latency. All exercises were videotaped and subsequently analyzed for performance parameters.

Data were analyzed using SPSS 16.0. Statistical analyses for significance were done using the Mann-Whitney U test for parametric data. Statistical significance was considered when p was less than 0.05.

4.3 Results

There were no technical problems using the network setup. Additionally, the network latency software (Shunra VE Desktop, Shunra Software Ltd, Philadelphia, PA) worked well and was able to emulate desired latencies.

The results of the straight cut test are shown in figure 20. There were no significant differences between the sequential and full latency task groups in time to perform a straight cut, except in trial 1 (0 ms versus 700 ms). A similar result was seen in the grasp steadiness test where mean number of off centre errors was recorded (figure 21).

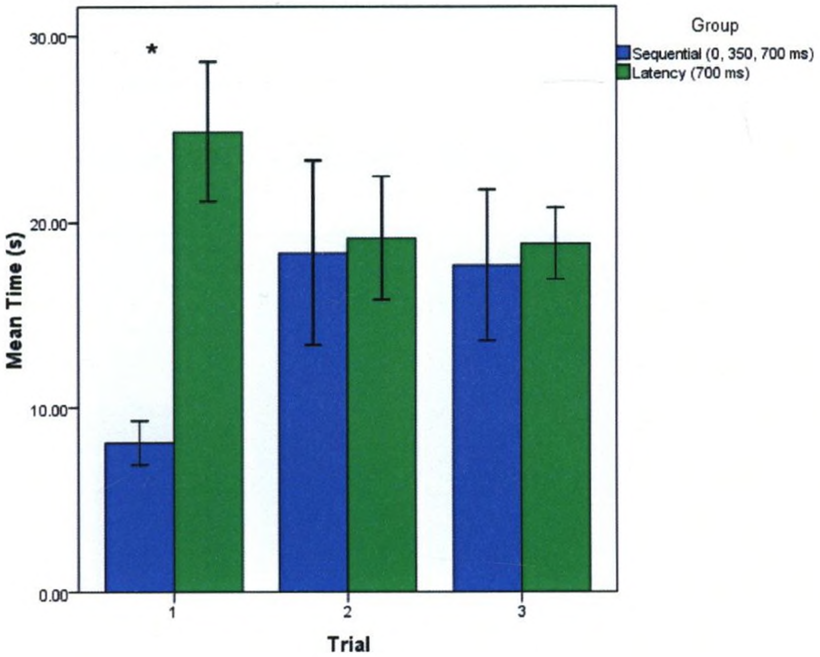

Figure 20. There was no significant difference in times to perform the straight cut between the sequential and latency groups except in Trial 1 (0 versus 700 ms). (* indicates $p < 0.05$)

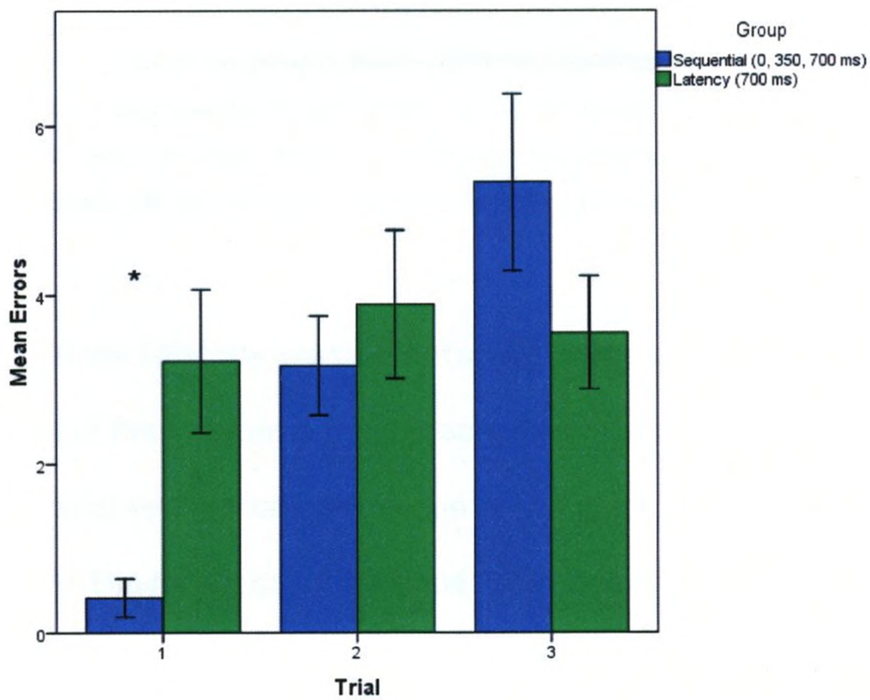

Figure 21. There was no significant difference in grasp steadiness errors between the sequential and latency groups except in Trial 1 (0 versus 700 ms). (* indicates $p < 0.05$)

In the Purdue pegboard test, the sequential group scored significantly better in number of pegs placed than the latency group in both trials 1 and 2 (zero versus 700 ms; 350 versus 700 ms respectively; figure 22).

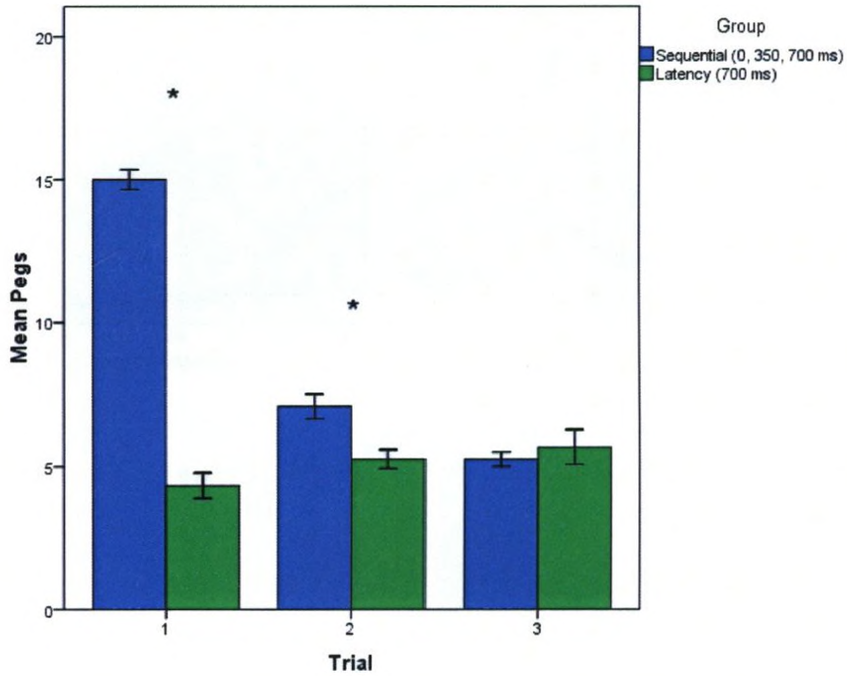

Figure 22. Sequential group subjects performed significantly better than the latency group in number of pegs placed in both Trials 1 and 2 (0 versus 700 ms and 350 versus 700 ms respectively). However, there was no significant difference between the groups when both experience 700 ms latency in Trial 3. (* indicates $p < 0.05$).

The results of the Fitts' law exercise are shown in the series of figure 23. Here the performance of the sequential group decreases over the trials of 0, 350, and 700 ms, as indicated by the increasing slope of line fit for this group (0.09; 0.32; 0.76 respectively). The reciprocal of the slope is the Index of Performance, IP, in bits/s. For the latency group, IP improved somewhat over the three trials of 750 ms (1.05; 1.08; 0.83). However, it is very similar to the IP of the sequential group by the last trial (0.76 versus 0.83).

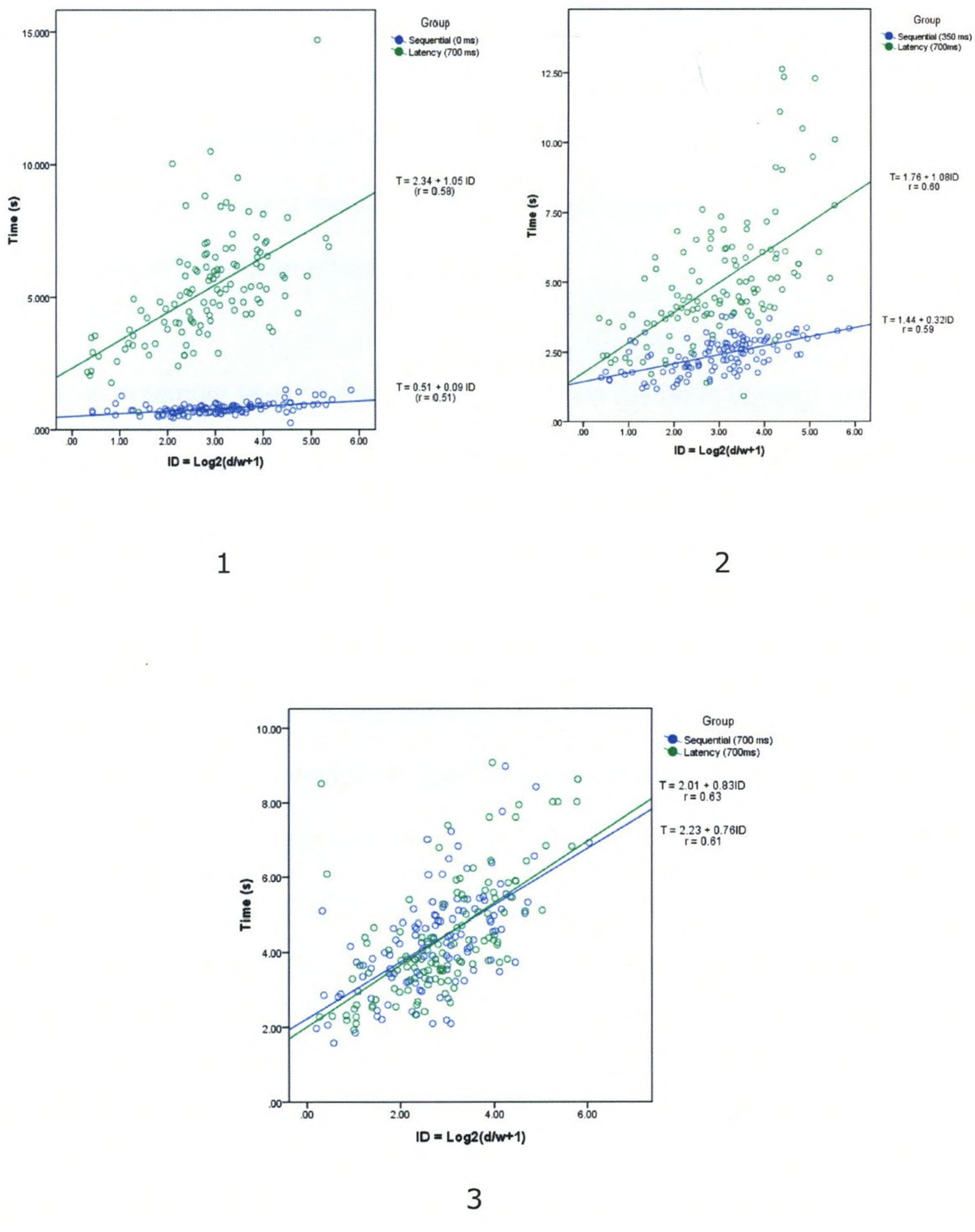

Figure 23. The Index of Performance (IP) of the sequential group (blue) compared to the latency group (green) is shown in Trials 1, 2, and 3. As the latency goes up for the sequential group, the slope of the Time versus Index of Difficulty line increases, indicating a decreasing IP. By the third trial, both groups are experiencing 700 ms and have similar IP.

4.4 Discussion

These experiments investigated different training options for telesurgery. Over the exercises conducted, there was no significant difference between groups training with sequentially increasing latency versus full latency only. The results suggest that either method could be effective.

Earlier work in remote teleoperation concentrated on methods to compensate for delay, rather than training the operator directly for it (2-5). In telesurgery, no such methods have been developed.

We broke surgery down into some very basic maneuvers. These included object placement, hold steadiness, straight line movement, and point to point targeting. All of the tests had been previously used and validated for health care or other disciplines (9 - 12). Surgery consists of more complex movements and higher levels of visual, tactile, and other processing. However, the tests used were a simple way to evaluate some 'finite elements' of surgery that are typical and reproducible.

The results of the Fitts' law test suggest that some training effect was occurring in the full latency group. Comparing the first and last trials, the slope of line fit decreased from 1.05 to 0.83 in this group. The reciprocal of the slope is the Index of Performance, IP, in bits/s. However, this improvement was very similar to that of the sequential latency group by the last trial (slope = 0.76). This again suggested that either technique produced similar effect. The correlation coefficient of the Fitts' prediction to the data was about 0.6. A further modification of Fitts' law which considers latency as a co dependent variable has been suggested (14, 15). This could be used in the future to refine performance measurements. We were unable to apply it here since latency was held constant in one group.

The historic method for surgical training is the apprenticeship model. The trainee is with more senior surgeons in the operating room. Learning and judgment evolves from years of observation, progressive practice, and trial and error.

However, in the era of robotic surgery and telesurgery, this method may be augmented. Although it is quite easy to observe, junior trainees will not get 'console time' on a \$1.5 million dollar robotic system easily. Methods of training must evolve with technology development. Today, robotic systems are similar to aircraft or other equipment, both in cost and complexity.

The apprenticeship model may need to change to become more effective. For telesurgery, our study suggests that trainees can prepare with or without latent environments. However, in both cases simulation was necessary. More sophisticated simulation models may show further differences in training methods. Additionally, more realistic simulation can provide a training ramp to transition junior personnel to real operating situations. Simulation can also train for new techniques, equipment operation, or abnormal / emergency procedures.

Both groups did equally well in the final trial of the exercises, whether they had experienced full latency earlier or not. The results may suggest that the exercise itself had a greater bearing on performance than did the addition of latency. If this is true, it may bode well for future telesurgery where the essential difference is latency. Our lab showed previously that complex surgery in animals could be performed equally well on ground- and satellite-based networks (16). Latency on the satellite network was much bigger than ground in these experiments (55 ms versus 600 ms).

References

[1] Sterbis J, Hanly E, Herman B et al. Transcontinental telesurgical nephrectomy using the da Vinci robot in a porcine model. Urol 2008; 71: 971-973.

[2] Gunn C, Hutchins M, Adcock M. Combating latency in haptic collaborative virtual environments. Presence 2005; 14(3): 313-328.

[3] Hamel W, Murray P. Observations concerning Internet-based teleoperations for hazardous environments. IEEE Int Conf Robot Autom 2001; 638-643.

[4] Brady K, Tarn T. Internet-based teleoperation. IEEE Int Conf Robot Autom 2001; 644-649.

[5] Ding G, Zhang J, He Y et al. VR-based simulation on material handling remote operation for engineering machine. IEEE Int Conf Imag Graph 2007; 984-989.

[6] Marescaux J, Leroy J, Gagner M, et al. Transatlantic robot-assisted telesurgery. Nature 2001; 413: 379-380.

[7] Anvari M, McKinley C, Stein H. Establishment of the World's First Telerobotic Remote Surgical Service. Annals Surg 2005; 241(3): 460-464.

[8] Kim T, Zimmerman P, Wade M, Weiss C. The effect of delay visual feedback on telerobotic surgery. Surg Endosc 2005;19: 683–686.

[9] Costa L, Vaughan H, Levita E, et al. Purdue Pegboard as a predictor of the presence and laterality of cerebral lesions. J Consult Psychol 1963; 27: 133-137.

[10] Fleishman E and Ellison G. A factor analysis of fine manipulative tests. J Applied Psychol 1962; 46: 96-105.

[11] Andres A, Sanchez E, Hildago J, et al. Appraisal of psychomotor skills of dental students at University Complutense of Madrid. Eur J Dent Edu 2004; 8: 24-30.

[12] Lentz G, Mandel L, Lee D, et al. Testing surgical skills of obstetric and gynecologic residents in a bench laboratory setting: Validity and reliability. Am J Obstet Gynecol 2001; 184: 1462-1470.

[13] Fitts P. The information capacity of the human motor system in controlling the amplitude of movement. J Experimental Psychol 1954; 47: 381-391.

[14] MacKenzie I, Ware C. Lag as a determinant of human performance in interactive systems. InterCHI 1993; 488-493.

[15] Jay C, Hubbold R. Quantifying the effects of latency on sensory feedback in distributed virtual environments. Proc Virtual Imag Sem 2006; 1: 9-16.

[16] Rayman R, Croome K, Galbraith N, et al. Robotic telesurgery: a real-world comparison of ground- and satellite-based Internet performance. Int J Med Robotics Comput Assist Surg 2007; 3: 111-116.

Chapter 5

Conclusions and future work

This chapter concludes the dissertation. Section 5.1 provides summary results for chapters 2, 3 and 4. Future work is discussed in section 5.2

5.1 Conclusions

The goal of this thesis was to define the requirements for telesurgery and identify its limitations. This was done by setting up a realistic communications network, using a robotic telesurgery platform to perform tasks and test network capabilities and using a simulation set up to test training effects. The tasks showed that telesurgery was feasible, and that the range of operation could extend 2000 km or greater. Either ground- or satellite-based communications would support emulated surgery. Additionally, trainees did equally well whether adapting from zero to higher latency or conducting full latency tasks only. The results are summarized below.

5.1.1 Set up for telesurgery and its experimental investigation (Ch. 2)

Before our work, telesurgery had been performed in anecdotal cases. There was no structured data on the tolerance of operators for latency while doing surgical tasks. This data would be important to define the feasibility of telesurgery. If the tolerance for latency was too low, the speed of network transmission and encoding would not accommodate telesurgery. A basic investigation of latency was required.

In this study, an industrial grade network with both ground and satellite capability was set up. A prototype, telesurgery capable robotic platform was used to perform dry lab surgical tasks. The platform was the only existing example worldwide, and had been used to perform a trans Atlantic patient case.

Eight test subjects performed tasks with transmission latency sequentially increasing from 0 to 600 ms, or randomly changing between 0 to 1000 ms. The subjects did the tasks with no significance difference in completion time in the sequential trials. During the randomized trials, tasks took significantly longer above 500 ms. There were no significant changes in error rates in either trial, except in one instance. This change was a *decrease* in errors at 500 ms in the sequential trial, which may be attributed to learning effects.

The study showed that both short and long term learning occurred over the four month duration. Short term learning was seen clearly as a subject encountered an increased latency. Task performance time was much higher during the first attempts at a higher latency, decreased markedly afterward, and then showed a plateau at this decreased level. Long term learning was seen in trials during the fourth month. Task times had decreased by the fourth month in all exercises.

This study showed that operators could perform well with transmission times of up to 500 ms. This equated to more than 5000 km of distance over an optical network, thereby providing a large range of capability. Operators could learn and adapt to the tasks. Therefore, further steps to investigate telesurgery were merited.

5.1.2 Emulation and evaluation of basic clinical procedures (Ch. 3)

Different telesurgery set ups had been used in the past. These were ground-based networks during proof of concept patient telesurgery. The networks were supported for a short term by industrial partners (1-5).

Such networks would be feasible in large cities or academic centers. However, in small or remote locations, satellite communication could be more realistic and cost effective. A study was needed to investigate the feasibility of ground- and satellite-based telesurgery. Additionally, performing procedures on animals could show how operators coped with increased surgical cadence and risks.

A full network providing both ground and satellite communications was established. The ZeusTS system was used for left internal mammary artery (LIMA) dissection in pigs. There was no significant difference in either length of arterial dissection or quality of surgery between the ground and satellite networks. Additionally, satellite-based telesurgery was not feasible below approximately 5 Mb/s bandwidth. This provided a baseline for minimum satellite requirements.

The study showed that telesurgery was feasible by both ground- and satellite-based Internet protocol. This can potentially increase the reach of telesurgery. Impoverished, remote, or endangered communities could have telesurgery access. Mobile or temporary satellite dishes are much more flexible than ground infrastructure. Therefore, such communities could be supported by telesurgery in the future.

5.1.3 Investigation of learning and training for telesurgery (Ch. 4)

The apprenticeship model has been the mainstay of training for surgery. Surgical residents learn by a graded progression of observation, task challenge, and interaction. By the end of residency, accomplished trainees can conduct full, complex procedures independently, can interact with the full surgical team (nurses, anaesthetists, support personnel), and can anticipate many steps ahead to judge requirements.

Robotic surgery and telesurgery will not easily support the apprenticeship model. Robot platforms are complex and expensive. The console is designed for a single user. It does not allow a trainee to interact or operate with mentors. Developing master-slave consoles for interaction would be advantageous.

Training for surgery must change to allow advancement. The advancement of surgery is established in robotic surgery (6). The training paradigm is even more significant when considering telesurgery.

This study investigated two ways of training for telesurgery. Simulation was used as a mainstay of the study. Telesurgery tasks were simulated in dry lab using typical manoeuvres at latencies between 0 and 700 ms. Subjects performed the tasks either with sequentially increasing latency (0, 350, 700 ms) or full latency only (700 ms). During the final trial of training, there was no significance difference in performance at 700 ms latency. This suggested flexibility in methods of training.

The study suggested that training for telesurgery should be reconsidered from the apprenticeship model. In practice, robotic surgery is usually conducted locally. In the future, occasional telesurgery will be done. This lends itself to a model in which trainees sequentially adapt to latency situations.

The study represented a shift from the training models of the past. Surgical simulation will become a significant aspect of residency training in the future. This study provided two potential methods of simulating telesurgery training, both of which were equally effective.

5.2 Future work in telesurgery

5.2.1 Advancing telesurgery platforms

Currently, there is only one clinical grade telesurgery platform. This platform has does not have full functional capability. The ZeusTS platform was used in proof of concept patient cases as well as in these experiments (1, 4). However, this platform is not commercially supported. There has been no support for Computer Motion technology since this company merged with Intuitive Surgical Inc. in 2003.

Intuitive Surgical Inc. has developed a telesurgery prototype platform and has used it in dry lab and animal studies (7). This platform is supported by the company. It is unclear whether it is being developed further. Limitations of the platform which are publicly known are that the distant operator cannot control the camera navigation of the robot, cannot clutch the robot in order to re centre console controls, and cannot activate the electrocautery functions of the robot. These are significant limitations which obviate full long distance control.

Robotic and telesurgery platforms need to be further developed. Beyond the shortcomings mentioned, the pace and capability of telesurgery platforms should increase in order to meet user demand. An increase in telesurgery capable units or prototypes will allow larger volumes of research to accelerate this technology.

5.2.2 Parameters for telesurgery networks

Communications infrastructure is continuing to grow. The demands of businesses are driving cheaper and faster bandwidth development worldwide. The implementation of Internet2 services last year marked a new stage in communications performance (8). With Internet2, academic centers can have the availability of up to 100 Gb/s bandwidth. Businesses or individuals will soon be able to order speeds from 50 Mb/s to 10 Gb/s with dynamic provisioning through established service providers.

These experiments suggest that 5 Mb/s is the minimum bandwidth needed for satellite telesurgery. In ground-based telesurgery, 8 to 15 Mb/s bandwidth would comfortably support telesurgery, even if dual video signals are needed to provide three dimensional vision (4, 7). The quality of service (QOS) provided by most Internet service providers is already very high, making the likelihood of communication disruption on the Internet backbone very low. Therefore, telesurgery communication may be become cost effective imminently.

Telesurgery networks would need to be partitioned and secure. Routine telesurgery between hospitals would require similar levels of security as financial and other private institutions. In remote communities, special consideration is needed to extend the Internet backbone. Satellite infrastructure may provide support to isolated groups in such instances.

5.2.3 Extending Fitts' law for telesurgery performance

Fitts' law is valuable for measuring performance in human computer interaction (HCI). For example, it is used when designing graphical user interfaces or other technologies that require target pointing and acquisition (9).

Within this thesis, Fitts' law was used to compare performance at sequentially increasing or constantly high latencies. The Shannon modification of Fitts' law was used:

$$ID = \log_2\left(\frac{D}{W} + 1\right)$$

where ID is the Index of Difficulty;
D is the distance between targets;
W is the target width.

The Index of Difficulty divided by the time to complete the movement (MT) will give a representation of the rate of task completion in bits / s. This is otherwise known as the Index of Performance (IP) and can be thought of broadly as the 'bandwidth' of the subject while doing the task:

$$IP = \frac{ID}{MT}$$

Rearranging and allowing for a non zero intercept 'a' of the subject, sometimes thought of as reaction time, gives:

$$MT = a + b \cdot ID$$

where a straight line plot results in the inverse of the slope 1/b representing the Index of Performance.

A modification of Fitts' law which accounts for latency in a system has been developed (10, 11). During a task with latency, the subject's movement can be surmised as a number of discrete movements, with each one being affected by the delay. (The idea of a number of discrete movements to complete a task during latency was also developed in section 2.2). Given this, latency would have a multiplicative effect on the Index of Difficulty:

$$MT = a + (b + cLAG) \cdot ID$$

When this modification was used, a closer correlation was found with latency up to 225 ms (10).

In the future, this modification can be used to measure performance in telesurgery. Importantly, higher lag in a telesurgery system may have severe impacts on performance according to this modification. This indicates that minimizing latency will be important. Additionally, predictive tools may be required to aid the operator in during high latencies.

5.2.4 Scenarios for telesurgery practice

The traditional concept of telesurgery contemplates an expert surgeon providing care to an isolated patient. However, there are several more likely scenarios in which telesurgery could be used.

Even senior staff surgeons sometime require consultation from colleagues for advice, new perspective, or assistance in difficult cases. In robotic surgery, many such instances will be encountered. Telesurgery can provide 'consultative services' over a long distance. Telesurgery will allow distant colleagues to collaborate or assist each other if difficulties are encountered. This would increase patient safety, and reserve surgeons' time only to cases which are particular for better outcomes or learning.

Telesurgery systems will increase in sophistication. The surgeon will be required to have knowledge of normal system operation, abnormal procedures, and emergency checklists. After initial familiarization and training, telesurgery may aid the surgeon with such 'home' operations. In this scenario, telesurgery may be used as a training method for the device itself, as well as for simpler robotic procedures. This support may be provided by the equipment manufacturer or another supporting group.

Residents and other trainees will need to learn surgery via robotic systems. In the future, surgery may consist of a mixture of conventional and robotic cases. In order to learn, both observation and simulation will be required. Telementoring is the observational form of telesurgery. Here, the observer does not control robotic instruments at a distance. Rather, the activity is restricted to learning from the distant surgical picture, and in some instances telestration pointing to areas of interest. Telementoring may become an important aspect of telesurgery for teaching and training.

5.2.5 Simulation and predictive techniques

Robotic surgery and telesurgery simulators should advance to this point to provide realistic training. This would also shift training away from the apprenticeship model and toward a more efficient and cost effective method. A large volume of work has been contributed to simulation of real processes. While this has occurred mostly in the aerospace industry, the recognition of medical simulation as an important training tool has begun (12, 13, 14). For a training method to be valid, it must fulfill a number of criteria outlined in chapter 1, section 2.6.

Already, simulators are being developed which replicate robotic instruments and tissue, similar to the da Vinci platform (15). Eventually, training may occur using the manufacturer's robotic console, but having the trainee interact with a virtual patient. This is similar to flight simulation at the present time. In this environment, there is no question of transference of skills, and abnormal or emergency procedures can be practiced with indemnity and no patient risk.

Several groups have studied ways to decrease or synchronize the effects of latency on multiple users (16, 17). Predictive techniques will never overcome a situation in which latency is combined with non uniform motion. However, prediction may help the user understand what will happen 'if I keep doing what I am doing now' (18). Further work on predictive displays for telesurgery would help the operator in a high latency environment.

5.2.6 Licensing and credentialing

Extending care via telesurgery means that robotic instruments may be moved across provinces, states, countries, or continents. This requires not only task proficiency through training, but also national or international accreditation. Telesurgery will likely begin in close 'pockets' of geography within the same country or its surrounding region. If results are promising, then telesurgery could expand quickly. The implications of global telesurgery are already being considered (19, 20, 21).

The need for telesurgery will determine how quickly these factors are resolved. In the near future, telesurgery may begin with increased pace. Training, credentialing, and licensing may become more salient at that time.

References

[1] Marescaux J, Leroy J, Gagner M et al. Transatlantic robot-assisted telesurgery. Nature 2001; 413: 379-380.

[2] Marescaux J, Leroy J, Rubino F et al. Transcontinental robot-assisted remote telesurgery: Feasibility and potential applications. Ann Surg 2002; 235(4): 487-492.

[3] Butner S, Ghodoussi M. Transforming a surgical robot for human telesurgery. IEEE Trans Robot Autom 2003; 19(5): 818-824.

[4] Anvari M, McKinley C, Stein H. Establishment of the world's fist telerobotic remote surgical service. Ann Surg 2005; 241(3): 460-464.

[5] Anvari M. Remote telepresence surgery: the Canadian experience. Surg Endosc 2007; 21: 537-541.

[6] Donias H, Karamanoukian R, Glick P et al. Survey of resident training in robotic surgery. Am Surg 2002; 68: 177-181.

[7] Sterbis J, Hanly E, Herman B et al. Transcontinental telesurgical nephrectomy using the da Vinci robot in a porcine model. Urol 2008; 71: 971-973.

[8] Anderson N. Internet2 hits 100Gbps, could scale 10x beyond that. Ars technica; http://arstechnica.com/news.ars/post/20071009-internet2-hits-100gbps-could-scale-10x-beyond-that.html

[9] Accot J, Zhai S. Beyond Fitts' law: Models for trajectory-based HCI tasks. Proc SIGCHI Conf Hum Fact Comput 1997; 295-302.

[10] MacKenzie I, Ware C. Lag as a determinant of human performance in interactive systems. InterCHI 1993; 488-493.

[11] Jay C, Hubbold R. Quantifying the effects of latency on sensory feedback in distributed virtual environments. Proc Virtual Imag Sem 2006; 1: 9-16.

[12] Carter F, Schijven M, Aggarwal R et al. Consensus guidelines for validation of virtual reality surgical simulators. Surg Endosc 2005; 19: 1522-1532.

[13] Rosenthal R, Gantert W, Hamel C et al. Assessment of construct validity of a virtual reality laparoscopy simulator. J Laparoendosc Adv Surg Tech 2007; 17(4): 407-413.

[14] Verdaasdonk E, Stassen L, Schijven M et al. Construct validity and assessment of the learning curve for the SIMENDO endoscopic simulator. Surg Endosc 2007; 21: 1406-1412.

[15] Balasundaram I, Aggarwal R, Darzi A. Short-phase training on a virtual reality simulator improves technical performance in tele-robotic surgery. Int J Med Robotics Comput Assist Surg 2008; 4: 139-145.

[16] Munir S, Book W. Internet-based teleoperation using wave variable with prediction. IEEE Trans Mechatron 2002; 7(2): 124-133.

[17] Arcara P, Melchiorri C. Control schemes for teleoperation with time delay: A comparative study. Robot Auton Sys 2002; 38: 49-64.

[18] Sheridan T. Space teleoperation through time delay: review and prognosis. IEEE Trans Robot Autom 1993; 9(5): 592-606.

[19] McLean T. The legal and economic forces that will shape the international market for cybersurgery. Int J Med Robotics Comput Assist Surg 2006; 2: 293-298.

[20] McLean T. The complexity of litigation associated with robotic surgery and cybersurgery. Int J Med Robotics Comput Assist Surg 2007; 3: 23-29.

[21] McLean T. Cybersurgery – An argument for enterprise liability. J Legal Med 2002; 23: 167-210.

Appendix A

Western

COPY

January 16, 2003

This is the Original Approval of this protocol
A Full Protocol Submission will be required in 2007

Dear Dr. Rayman:

Your "Application to Use Animals for Research or Teaching" entitled:

"Assessing the Feasibility and Safety of Long Distance Telesurgery"
Funding Agency-- CSTAR - Grant #LHRF7113

has been approved by the University Council on Animal Care. This approval expires in one year on the last day of the month, but the protocol number will remain the same. The number for this project is 2003-010-01.

1. This number must be indicated when ordering animals for this project.
2. Animals for other projects may not be ordered under this number.
3. If no number appears please contact this office when grant approval is received.
   If the application for funding is not successful and you wish to proceed with the project, request that an internal scientific peer review be performed by the Animal Use Subcommittee office.
4. Purchases of animals other than through this system must be cleared through the ACVS office. Health certificates will be required.

ANIMALS APPROVED					FOR 4 YEARS	PAIN LEVEL
Porcine -	Domestic	20-50 kg	M (barrow)	-	20	B

STANDARD OPERATING PROCEDURES
Procedures in this protocol should be carried out according to the following SOPs. Please contact the Animal Use Subcommittee office (661-2111 ext. 86770) in case of difficulties or if you require copies. SOP's are also available at http://www.uwo.ca/animal/acvs
310 Holding Period Post Admission
320 Euthanasia

REQUIREMENTS/COMMENTS
Please ensure that individual(s) performing procedures on live animals, as described in this protocol, are familiar with the contents of this document.

1. Please ensure that all personnel (except the PI) working with these animals have attended the Animal Care and Use Lecture and appropriate workshops.

c.c. Approved Protocol - R. Rayman, L. Denning, W. Lagerwerf
Approval Letter - W. Lagerwerf, K. Perry, L. Turner

University of Council on Animal Care • The University of Western Ontario
Animal Use Subcommittee • Health Sciences Centre • London, Ontario • N6A 5C1 • Canada

Western

COPY

January 12, 2004

This is the 1st Renewal of this protocol
A Full Protocol Submission will be required in 2007

Dear Dr. Rayman:

Your "Application to Use Animals for Research or Teaching" entitled:

"Assessing the Feasibility and Safety of Long Distance Telesurgery "
Funding Agency– CSTAR - Grant #LHRF7113

has been approved by the University Council on Animal Care. This approval is valid from February 1, 2004 to January 31st, 2005. The number for this project remains as 2003-010-01.

1. This number must be indicated when ordering animals for this project.
2. Animals for other projects may not be ordered under this number.
3. If no number appears please contact this office when grant approval is received. If the application for funding is not successful and you wish to proceed with the project, request that an internal scientific peer review be performed by the Animal Use Subcommittee office.
4. Purchases of animals other than through this system must be cleared through the ACVS office. Health certificates will be required.

ANIMALS APPROVED					FOR 1 YR.	PAIN LEVEL
Porcine -	Domestic	20-50 kg	M (barrow)	-	10	B

STANDARD OPERATING PROCEDURES
Procedures in this protocol should be carried out according to the following SOPs. Please contact the Animal Use Subcommittee office (661-2111 ext. 86770) in case of difficulties or if you require copies. SOP's are also available at http://www.uwo.ca/animal/acvs
310 Holding Period Post Admission
320 Euthanasia

REQUIREMENTS/COMMENTS
Please ensure that individual(s) performing procedures on live animals, as described in this protocol, are familiar with the contents of this document.

c.c. Approved Protocol - R. Rayman, L. Denning, W. Lagerwerf
Approval Letter - L. Denning, W. Lagerwerf,

University of Council on Animal Care • The University of Western Ontario
Animal Use Subcommittee • Health Sciences Centre • London, Ontario • ...

Permission is hereby granted to reproduce the article requested as part of the
specified thesis. The article may be incorporated into the specified thesis only
and may not be stored separately or made available independently from the thesis
in any way.

Please note also that the published Wiley PDF version may not be placed onto any
personal website, institutional open access repository, or other externally
accessible website or database of any kind. If the article is to be placed
online, a preprint version must be used. This must be the version originally
submitted for publication (i.e. before peer review).

Any third party material is expressly excluded from this permission. If any
material appears within the article with credit to another source, authorisation
from that source must be obtained.

This permission does not include the right to grant others permission to
reproduce this material.

Proper credit must be given to our publication.

Credit must include the following components:
Title of the Journal, article title, author(s) name(s), Copyright [symbol]
[copyright year] John Wiley & Sons Limited. Reproduced with permission.

Yours sincerely

Duncan James
Permissions Coordinator
John Wiley & Sons Ltd.
The Atrium
Southern Gate, Chichester
West Sussex, PO19 8SQ
UK

-----Original Message-----
From: republication [mailto:republication@wiley.co.uk]
Sent: 26 June 2008 15:52
To: Permission Requests - UK
Subject: Republication Request Form

A00_Salutation: Dr
A01_Initials: R
A02_Last_Name: Rayman
A03_Company_Name: The University of Western Ontario
A04_Address: 701 - 19 King St

A05_Address_Line_2:
A06_City: London
A07_State:
A08_Zip: N6A 5N8
A09_Country: Canada
A10_Contact_Phone_Number: 519 432 9927
A11_Fax: 519 432 7945
A12_Emails: raymanr@aol.com
A13_Reference:
A14_Book_Title: The International Journal of Medical Robotics and Computer
Assisted Surgery
A15_Book_Author:
A16_Book_ISBN:
A17_Journal_Month: June
A18_Journal_Year: 2007
A19_Journal_Volume: 3
A20_Journal_Issue_Number: 2
A21_Copy_Pages: 111-116
A22_Maximum_Copies: 4
A23_Your_Publisher: The University of Western Ontario
A24_Your_Title: PhD thesis
A25_Publication_Date: September 2008
A26_Format: print
A27_If_WWW_URL: http://
A28_If_WWW_From_Adopted_Book: No
A29_If_WWW_Password_Access: No
A30_If_WWW_Material_Posted_From:
A31_If_WWW_Material_Posted_To:
A32_Print_Run_Size:
A33_If_Intranet_From_Adopted_Book: No
A34_If_Intranet_Password_Access: No
A35_If_Intranet_Material_Posted_From:
A36_If_Intranet_Material_Posted_To:
A37_If_Software_Print_Run:
A38_Comments_For_Request: I am the author of this work. I will be including
this work within my PhD thesis. Thank you.