Robot-Assisted Minimally Invasive Surgery: The Importance of Human Factors Analysis and Design

CAROLINE G.L. CAO, Ph.D.
DIRECTOR, HUMAN FACTORS PROGRAM
ASSISTANT PROFESSOR, DEPARTMENT OF MECHANICAL ENGINEERING
TUFTS UNIVERSITY SCHOOL OF ENGINEERING
MEDFORD, MASSACHUSETTS

GARY S. ROGERS, M.D.
PROFESSOR OF SURGERY & DERMATOLOGY
TUFTS UNIVERSITY SCHOOL OF MEDICINE
ADJUNCT PROFESSOR
TUFTS UNIVERSITY SCHOOL OF ENGINEERING
MEDFORD, MASSACHUSETTS

ABSTRACT

Success in robotic minimally invasive surgery (MIS) has been limited despite the innovations in robotic technology for surgical applications. Human factors engineering approach to the design and implementation of this technology is major to improving system performance and patient safety. The engineering discipline of human factors involves the study of factors and development of tools that enable human interaction with systems in a safe and effective manner. Human factors contribution is important to the product design life cycle, as it supports the design of a product capable of supporting, extending, and transforming user work in a cost-effective and timely fashion. A framework for modelling the interaction between the surgeon and technology in MIS is presented. This approach allows for identification of requirements and constraints at the physical, functional, and cognitive levels, which in turn guides the design of the technology and its interface. The human factors approach is expected to increase the effectiveness of the technology when deployed.
INTRODUCTION

Advances in robotics and computer-based technology have enabled much complex work in surgery to be automated, performed, or both, by way of remote control. The development of robotic systems for minimally invasive surgery (MIS) is generating considerable excitement in medicine. From the technological point of view, this development follows the natural progress of advancements from traditional methods of surgery-MIS to robotic-MIS. We know and appreciate the added benefits of MIS over traditional open surgery, such as reduced pain and suffering and faster recovery for the patient. However, limitations of the technique continue to exist. Some of these limitations are a restricted field of view in two-dimensions (2D) of a monitor, increased visuomotor transformations, limited degrees of freedom, and reduced tactile feedback for the surgeon. The combination of these physical, precision, safety, and visuomotor constraints makes MIS a difficult task to learn and master. This difficulty is evidenced by the large number of medical errors associated with this technology. Some of these “medical errors” have been related directly to poor design of technology and rapidly changing technology, as well as insufficient knowledge or training of surgeons. Some of these injury-causing errors do not exist in open surgery. For example, insertion of the Veress needle and trocar in laparoscopic surgery can cause injury due to lack of direct visual guidance, or omitting to place clips on the cystic artery in a cholecystectomy procedure. Other errors are associated with the use, or mis-use, of unfamiliar instruments, such as applying too much force with the graspers, tearing the gallbladder, or leaving the hook knife activated between steps in the surgical procedure.

Robotic surgery is expected to add many of the limitations in MIS. For example, robotics can increase dexterity by increasing the degrees of freedom for manipulation, or automate those surgical tasks difficult to perform remotely. Furthermore, robotics can increase the precision and accuracy of fine motor performance by stabilizing tremor, or scaling down the movements made by the surgeon’s hands. Robotic surgery also promises to restore the sense of touch to the surgeon through haptic interfaces. Haptics, or more specifically, force feedback, has been shown to increase speed and accuracy in teleoperation tasks.

Successful robotic applications in MIS have been limited despite innovations in robotic technology for surgical applications. Obstacles to development and implementation of the technology remain in the complex operating room environment. These obstacles are related primarily to coupling of the technology with the human operator, i.e., the surgeon. Being removed from the surgical site, a surgeon does not receive the full range of sensory information obtained normally through vision, audition, vestibular apparatus, haptics, kinesthetics, and olfactory senses. Rather, most of the available information is received through the visual channel. Even that modality, however, is based on video images of the remote site, which typically provide a restricted field of view and limited depth information from a frequently poor vantage point. These limitations can affect performance of surgical tasks that require precision and accuracy in manipulation. Thus, the physical barrier imposed by technology also represents a perceptual barrier for the surgeon, by increasing the information-processing demands. Successful application of robotics in MIS relies not only on innovative technology, but also the effective integration of this technology into the complex human-machine system in the operating room environment. The objective of this chapter is to discuss the role of human factors in analysis and design of surgical robots. Examples illustrate how human factors analysis and design have been implemented successfully in the MIS domain.

Effective technology can improve the performance of the system with increased reliability and precision. However, it also can create unexpected interactions and new forms of errors. High error rates in surgery, in particular those associated with technology in MIS, have been documented. Furthermore, robotics can increase the precision and accuracy of fine motor performance by stabilizing tremor, or scaling down the movements made by the surgeon’s hands. Robotic surgery also promises to restore the

HUMAN FACTORS ENGINEERING

What is Human Factors Engineering?

What does the study of human factors encompass? Human factors is the discipline of engineering that involves the study of factors and development of tools that enable human interaction with systems in a safe and effective manner. The Human Factors and Ergonomics Society (HFES) Task Force on Health Care defines human factors as a discipline that "discovers and applies information about human behaviors, abilities, and other characteristics to the design of tools, machines, systems, tasks, jobs, and environments for productive, safe, comfortable and effective human use." As products become more technologically sophisticated, they frequently become more difficult to use. Poor design is common, as evidenced by the level of frustration in using everyday things. In many cases, human factors is generally not considered in the design process until the end of the product development cycle, when it becomes obvious that human factors input is critical for success of the product. Unfortunately, bringing in human factors expertise at the end of the development cycle creates the undesirable situation of having a one's design criticized. Changes to the design at that stage are costly and time consuming. Therefore, it is more cost-effective and beneficial to introduce human factors at the beginning of the product design cycle. In a typical product-design life cycle, the contribution of human factors analysis supports the design of a product capable of supporting, extending, and transforming user work in a cost-effective and timely fashion.

Typically, the systems engineering process consists of the activities listed in Table 1.

1. Requirements analysis
2. Conceptual design
3. Iterative design and testing
4. Hardware and software development
5. Systems production
6. Implementation and evaluation
7. Maintenance and operations
8. System disposal

Even though the process is listed here as a series of steps, implying
sequential order, the process actually involves feedback loops and iterations within and among several steps in practice. The general idea is to design a usable new system—or improve upon an existing design. The system must be identified and described at the physical level (i.e., what the system contains), functional level (i.e., what the system does), and operational level (i.e., how the system is used). The requirements and constraints also need to be determined so they can be addressed adequately by the new design. These activities may require several iterations to balance tradeoffs. After the design is complete, evaluation and validation can be conducted. If adjustments need to be made to the design, more iterations are required. In reality, three intertwining phases form the basic framework for an analysis and design activity. The three boxes, each of which represent one of these three phases, are joined by lines with bi-directional arrows that indicate the back-and-forth flow of activities and information in the iterative process of analysis and design (Fig. 1).

**APPLICATION OF HUMAN FACTORS IN MIS**

Robotic systems for surgery have seen rapid development, but only tentative acceptance by the general public. Initially, the most common use of robots in MIS is for positioning the laparoscope using voice control, such as the Automated Endoscopic System for Optimal Positioning (AESOP™, Intuitive Surgical, Inc., Sunnyvale, CA, USA). The benefit of using a robot for this task is that it does not fatigue, does not shake, and can be controlled verbally by the primary surgeon. This robot greatly increases the efficiency of the visualization process, as the surgeon controls exactly what is being viewed, and brings the procedure closer to a cost-effective "solo operation" where fewer surgeons are needed in the operating room. More sophisticated robotic systems have been developed that have a larger role in the surgical process. The Food and Drug Administration (FDA) has approved at least two systems, DaVinci™ (Intuitive Surgical, Inc., Sunnyvale, CA, USA) and Zeus™ (Intuitive Surgical, Inc., Sunnyvale, CA, USA), for clinical use. Little is known about their performance and efficacy from a human-factors perspective.

### Table I

**Product Development Life Cycle and Associated Human Factors Activities**

<table>
<thead>
<tr>
<th>Stages in Product Life Cycle</th>
<th>Human Factors Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Requirements analysis</td>
<td>User analysis</td>
</tr>
<tr>
<td></td>
<td>Function analysis</td>
</tr>
<tr>
<td></td>
<td>Preliminary task analysis</td>
</tr>
<tr>
<td></td>
<td>Environment analysis</td>
</tr>
<tr>
<td></td>
<td>Identify user preferences and requirements</td>
</tr>
<tr>
<td></td>
<td>Provide input for system specifications</td>
</tr>
<tr>
<td></td>
<td>† make sure objectives and functions match user requirements;</td>
</tr>
<tr>
<td></td>
<td>† provide ergonomic criteria</td>
</tr>
<tr>
<td>2. Conceptual design</td>
<td>Functional allocation</td>
</tr>
<tr>
<td></td>
<td>Support the conceptual design process</td>
</tr>
<tr>
<td>3. Iterative design &amp; testing</td>
<td>Task analysis</td>
</tr>
<tr>
<td></td>
<td>Interface design</td>
</tr>
<tr>
<td></td>
<td>Develop prototypes</td>
</tr>
<tr>
<td></td>
<td>Heuristic evaluation (design review)</td>
</tr>
<tr>
<td></td>
<td>Additional evaluative studies/analyses</td>
</tr>
<tr>
<td></td>
<td>† cost-benefit analysis for alternatives;</td>
</tr>
<tr>
<td></td>
<td>† trade-off analysis;</td>
</tr>
<tr>
<td></td>
<td>† workload analysis;</td>
</tr>
<tr>
<td></td>
<td>† simulations or modelling;</td>
</tr>
<tr>
<td></td>
<td>† safety analysis</td>
</tr>
<tr>
<td></td>
<td>Usability Testing</td>
</tr>
<tr>
<td>4. Hardware and software development</td>
<td>Develop or provide input for support materials, such as manuals</td>
</tr>
<tr>
<td>5. Systems production</td>
<td>Evaluate fielded system</td>
</tr>
<tr>
<td>6. Implementation and evaluation</td>
<td>Monitor system performance over time</td>
</tr>
<tr>
<td>7. Maintenance and operations</td>
<td></td>
</tr>
<tr>
<td>8. System disposal</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 1. Iterative analysis and design process in product life cycle.**
because these robotic systems are novel to most researchers working in the field of human factors and ergonomics. Few studies have been conducted to compare the performance of robotic surgery to 'traditional' MIS. Case studies and institutional reviews have been published on robot-assisted laparoscopic surgery, the successful completion rates were similar to those of human laparoscopic surgery. The robot, however, was almost never faster than its human counterpart.

As with any new area of technological innovation, knowledge regarding best practices is usually gained only after a dramatic event that indicates a need for better design. Recently, several studies reported on the high number of injuries and deaths due to medical errors. The conservative estimation was that, in the U.S., at least 44,000 deaths annually and $17-$29 billion are associated with adverse events. The reports also indicated that two-thirds of these injuries and deaths were preventable. In particular, 44% of the errors that resulted in adverse events were due to technical errors. From a human factors perspective, errors are frequently the outcome of a poor match between the design of the technological system and human characteristics in the system. Much of what is known about the human factors issues in MIS has been gained through systematic analysis by human factors researchers. Not much is yet known about robotic MIS. However, the expectations are that knowledge can be extrapolated from the area of MIS into robotic MIS. A framework is presented for modeling the interaction between the surgeon and technology in MIS and examples of how the human factors approach can contribute to the design of an effective tool.

**MODELING MIS USING THE INFORMATION-PROCESSING MODEL**

Surgical procedures are more complex to perform endoscopically than open for the surgeons. Compared to traditional open surgery, minimally invasive procedures impose additional safety concerns and precision requirements, as well as greater physical and visuomotor constraints on the surgeon. These additional safety issues are due to restricted access to the operative site within the respective body cavities by way of visual, tactile, and motor limitations. The very tools that allow surgical operations to be performed with minimal invasiveness present both major physical and perceptual barriers. An understanding of the task requirements, task constraints, and information-processing demands on the surgeons in remote manipulation, as well as the interaction between the surgeon and their instruments in performing endoscopic surgery tasks, is useful for designing telemedicine systems and instrumentation.

From a human factors point of view, humans can be viewed as information-processing systems. As such, human information-processing efficiency can be associated with the amount of information the operator can process per unit time. Also, task difficulty can be viewed in terms of the amount of information and the rate at which information is presented. When information presented exceeds the capacity to process it, errors occur. In Wickens’ and Hollands’ model of human information processing (Fig. 2), the flow of information and stages of information processing can be simplified and identified.
1. Sensory processing of stimuli through the visual, auditory, proprioceptive, or kinaesthetic senses.
2. Perceptual encoding, where decisions are made to assign stimuli to separate perceptual categories, or where analogue perception (as in driving) takes place.
3. Decision making, where decisions are made by the human operator to store information for later use (commit to long-term memory), elicit a motor response, or both.
4. Response execution requires the call-up, release, and generation of motor sequences with muscle activation. (These responses are executed either successfully or unsuccessfully.)
5. Feedback and information flow are mostly visual, but also include important tactile as well as auditory information.

Note that this information flow need not be initiated only by external stimuli; it can arise internally from memory. In the case of surgery, surgeons invoke their long-term memory to plan surgical procedures, as well as working memory for intraoperative decision making.

In information-processing terms, therefore, MIS "telemanipulation" involves recognition, encoding, transformation, decoding, and comparison—integrated with anticipation, past experience, and feedback—for response selection and execution. Throughout the operation, the operating surgeon orchestrates the surgical team by issuing orders while attending to the task of performing surgery. The surgeon's task is to remotely manipulate tissue states and recognize the changes effected, with minimum error and maximum control, although not at any particular speed. This task requires a combination of highly complex cognitive processes, composed of attention, knowledge, recognition, decision-making, and motor execution, all contributing to continuous, on-line, closed-loop control. Wickens' model of human-information processing can be modified to describe the cognitive processes that underlie the decisions for motor responses in MIS (Fig. 2).

As most of the global decisions for surgery have been made before entering the operating room, the surgeon's cognitive task during surgery consists of two parallel goals: 1) to execute a planned sequence of actions based on knowledge of the surgical procedure, and 2) to detect and correct deviations from the pre-planned course of action, as the operation proceeds, based on new information from the environment, as well as declarative knowledge of anatomy and case-specific details. As the surgeon is operating under uncertainty and risks, as well as time and energy pressures, these two goals may conflict. Surgical plans are modified as the operation progresses, much like reactive problem solving in a dynamical control system. Each decision to select a particular response is based on the previous response, and perception of its feedback (filtered by the 2-D display of the surgical field).

In this respect, the surgeon's on-line decision making evident of cognitive control from different levels at each stage of performing MIS. They exhibit features of rule-based and knowledge-based behaviour, in addition to skill-based behaviour (Fig. 3). Even in expert surgeons, surgical manipulations are slow, methodical, and sometimes hesitant when performing well-practiced surgical tasks. Performance of the surgical manipulations suggests increased information processing such as decision making, accessing stored rules from memory, and mental rotations, perhaps due to the visuomotor constraints in the task. Rasmussen's
Figure 4. Hierarchical decomposition of a fundoplication from steps to substeps and tasks.
model for multi-levels of cognitive control over human behaviour can be applied to each step of the surgical procedure to describe the surgeon's behaviour. Thus, the surgeon's cognitive processes can be inferred by analyzing the behaviour during various stages of the procedure.

The result of information-processing limitations inherent in performing motor tasks in general are:

1. not knowing what to expect from one's own action,
2. insensitivity to sensory/perceptual discrimination, and,
3. lack of proficiency in performing appropriate actions.

In MIS, these limitations manifest themselves due to the filtered stimuli upon which the surgeon relies to make decisions for subsequent actions. Schueman and Pickleman reported that, in addition to manual dexterity, the surgeon's ability to 'see' the relevant anatomy of the operative site is important. The 'expert' surgeon quickly identifies important landmarks in the incision, and mentally organizes multisensory data and actions during the course of the surgical procedure to produce smooth and efficient sequences of responses.

**FIELD STUDY FOR REQUIREMENT ANALYSIS**

To illustrate the importance of human factors analysis in the design cycle, a field study of fundoplication beginning with a hierarchical task analysis is presented. A hierarchical task analysis produces a plan of action, that specifies the order or sequence of actions, and conditions under which the tasks are performed to achieve the goals. The analysis also can specify time constraints and highlight the information or knowledge needed for the tasks, as well as equipment needed. These are presented as direct quotes from surgeons during field studies.

A hierarchical decomposition of the fundoplication procedure, with increasing levels of details, from surgical steps, substeps, tasks, sub-tasks, down to the level of motions is shown in Figure 4. Surgical steps are clearly defined by operational definition of beginnings and endings (Table II). These steps in sequence represent the high-level surgical procedure. At this high level, surgeons' diagnostic and surgical decisions are not concerned with information and constraints specified at the lower levels.

Each step is further decomposed into substeps, action sequences taken to accomplish the surgical goals defined in the above step. At this level of decomposition, more details are specified in terms of constraints for the goal of the particular step at the level above. For example, in dividing the peritoneum in a fundoplication, the substeps are 'locate' and 'divide' (see Fig. 4). These substeps have specific safety and precision constraints that dictate how the goal at the step level can be achieved. Similarly, these substeps are constrained by basic surgical tasks clearly and individually distinct. For example, suturing and tying knots were two basic surgical tasks to 'join the cruze' in a fundoplication.

The 'higher goals', as defined in Figure 3, represents the goals of the surgical procedure. In an anti-reflux procedure, this goal is to use part of the fundus of the stomach to form a wrap around the oesophagus. (The wrap acts as a sphincter to prevent reflux from the stomach back into the oesophagus.) These high-level goals impact on the outcome of behaviour at the knowledge-based level. However, the plan is not so rigid as to contain all requisite surgical tasks in a specified sequence. Depending on the success of the action taken at each step, the surgeon makes adjustments to the choice of subsequent actions based on judgment of the state of affairs. With each surgical step in the procedure, the surgeon, highly skilled at performing basic surgical tasks (e.g., suturing at the skill-based level of cognitive control), also is guided by rule-based and knowledge-based levels of cognitive control.

Beginning with step 2 of the procedure, all the visual information about the state of the operation is derived from the video monitor. Therefore, depending on the spatial compatibility between the visual field and operative field, the surgeon must mentally rotate one field to match the other, as well as transform the mapping into a body-cen-
Figure 5. Comparison of durations of surgical steps in fundoplication, with and without cutting the short gastrics before wrapping the fundus.

Duration of surgical steps in the Fundoplication

<table>
<thead>
<tr>
<th>Surgical Steps</th>
<th>With Cut</th>
<th>Without Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prepare patient</td>
<td>10 min.</td>
<td>15 min.</td>
</tr>
<tr>
<td>Divide peritoneum</td>
<td>20 min.</td>
<td>25 min.</td>
</tr>
<tr>
<td>Expose crura and GE junction</td>
<td>30 min.</td>
<td>35 min.</td>
</tr>
<tr>
<td>Repair crura</td>
<td>40 min.</td>
<td>45 min.</td>
</tr>
<tr>
<td>Divide short gastrics</td>
<td>45 min.</td>
<td>50 min.</td>
</tr>
<tr>
<td>Wrap fundus</td>
<td>50 min.</td>
<td>55 min.</td>
</tr>
<tr>
<td>Close</td>
<td>60 min.</td>
<td>65 min.</td>
</tr>
</tbody>
</table>

Veteran coordinate system for some visuo-motor integration for successful manipulation. The restricted field of view afforded by the endoscopic camera forces surgeons to rely on their memory and knowledge of the abdominal anatomy to orient themselves. The camera's changing point of view, magnification of the image on the monitor with movement of the endoscope, and altered spatial relationship between display space and operative space, also require the surgeon to mentally orient and recalibrate the operative field with each change. The surgeon cannot rely solely on skill-based behavior to accomplish task goals. Rules are used to establish orientation before proceeding.

_Surgeon_: "See, um, it is really hard to tell where I am, so part of what I can do is even just touching that sutures very lightly I can judge whether I am in front of it or behind it."

Step 3 of the Fundoplication procedure is to expose the crura and the O.G. or G.E. junction. This step requires the surgeon to locate the anatomical landmarks, isolating the structures most crucial to the operation. In so doing, connective tissue joining the stomach and oesophagus to the diaphragm is dissected to form a gap in the diaphragm. This step is especially demanding in terms of attention resources and memory for recognition of structures and landmarks, as illustrated by the following verbal exchange between the operating surgeon and assisting surgeon.

_Surgeon_: "That is why it is so important to get down on the right crux cause that sort of allows you to see the left crux—now that allows us to see oesophagus in the front—step that is where you are."

_Assist Surgeon_: "I keep getting temporally lost in the bush."

_Surgeon_: "Yeah, it is until you get there—there is a sense of relief when you see the right landmark, when all of a sudden you see where you want to be."

Step 6 of the procedure is the major step to completing the goal of the operation—wrapping the fundus around the oesophagus. In this step, the fundus of the stomach is grasped, pulled underneath and around the oesophagus to form the wrap. Sutures are then placed in the wrap to anchor it. This particular step involves a high degree of hand-eye coordination, as well as haptic coordination of manipulation between surgeons. Both surgeons must perform mental rotations of the visual space with the operative space independently, as they are standing in different locations around the patient, to match each other's transformed map. A great deal of verbal communication exists between the co-operating surgeons, especially at this step.

_Surgeon 1_: "This always feels like it was never, doesn't it Peter, when you've got that window."

_Surgeon 2_: "Oh yeah."

_Surgeon 1_: "You start to feel a lot more comfortable that is the key to the operation."

_Surgeon 2_: "Well once you meet from the side you know you are fine—it is just that preliminary dissection to recognize, these structures—getting your planes."

_Surgeon 1_: "From our experience that really, that was the one time we screwed up—I screwed up was when we had a real hard time getting that anatomy established."

_Surgeon is having problems suturing:
- Firstly, the camera is not centered, now
- Secondly the table is too high. I am getting tennis elbow."

_Surgeon_: "Come on in Erik, when you are suturing, 2D is much worse when you are far away."

_Surgeon 1_: "This is where the 2D is a
problem, you don't have to be very far from the lens to lose your view."

Surg: 2: "Well, the problem is the direction in which I see—where are you going (Surgeon 1 adjusts scope)—this doesn't help."

Time and Motion Analysis
Another example of the potential power of the human factors engineering approach is demonstrated by the comparison of two different techniques for performing a fundoplication. In one technique, the short gastric vessels were cut before the step of wrapping the fundus around the esophagus. In another, the short gastric vessels were left intact. Figure 5 shows that the subsequent steps to cut the short gastric vessels were faster than when the short gastrics were not cut, which suggests it was more difficult to do the wrap in the latter case. This information can be used in conjunction with patient outcome results to support the choice of one technique over another. Clearly, the decomposition hierarchy of surgical procedures allows for an objective and systematic approach to assessing performance.

Hierarchical decomposition of surgical procedures is a powerful analytic approach that offers a framework for structuring the complex environment within which the surgeon and technology interact. It can be used to study the relationship between goals and actions at various levels of the hierarchy, with different sets of constraints. This information is useful for the design of surgical training systems, with individual modules representing the level of the hierarchy and the appropriate motion for the trainee's experience. This approach has the advantage of focusing the surgeon's attention on the information most relevant to training, given the skill level and past experience. It has the versatility to be extended to measuring surgical skill performance in an objective and quantitative manner. Also, the approach can be applied in assessment of new technology, by measuring impact on surgical performance outcome, related directly to patient outcome.

CONCLUSION
Although surgeons are skilled at performing basic surgical tasks, highly manual in nature, their behaviors in different surgical procedures pass smoothly across the three levels of cognitive control, depending on availability of environmental cues and attentional resources. Although knowledge-based behavior guides the surgeon's high-level decisions, this behavior operates in the background. Rule-based behavior is most prominent, arising primarily from the visuomotor constraints of remote vision and remote manipulation, while skill-based behavior executes the basic surgical tasks.

Although errors have not explicitly been a topic of discussion in this paper, it is clear that the potential for errors, mistakes, or slips at any point during each of the surgical steps is high. In laparoscopic hernia repair, if the image of the operative field is rotated, the vas deferens may mistakenly be clipped instead of the Cooper's liga-

ment. Alternatively, the scissors may be closed on the vessel adjacent to the suture to be cut. Another example is that the cautery probe may be moved to the right instead of to the left and puncture the spleen. These risks are inherent in any surgical procedure, but are arguably more likely in MIS, where surgeons have increased information-processing demands due to the physical and visuomotor constraints of the task. Therefore, future efforts in developing endoscopic and telepresence technology should take into consideration the limitations of human information-processing capabilities, and minimize the additional information-processing demands imposed on the surgeon. A compatible display and control system for visualization, and manipulation in the telepresence environment can mean the difference between life and death in telepresence.

Use of robotics and automation in surgery is relatively new. Aside from the celebrated heroic achievement, there has been little documentation of the effectiveness of this technology in the complex environment of surgery. However, much publicity has revolved around the failure in adopting robotics in the operating room. The general misconception is that the robotic devices are technologically sophisticated and functional as designed, but that the human surgeon controlling the robot is incompetent. This notion leads proponents of robotics and automation to strive to incorporate even more automation in an effort to design the error-inducing human out of the loop. We caution the engineering community from blindly pursuing this direction. The medical community can learn a great deal from other industries where automation has become an integral part of the complex systems (e.g., aviation, nuclear-power generation, process control, etc.). A human factors approach in the analysis and design of surgical robots would be well advised.

After successfully integrated, robotic surgery represents another high point of technological achievement in the history of surgery. Expectation is that robotics technology, with its promise to extend human capabilities and enhance performance, will enable more efficient techniques to be performed, and can be incorporated into other surgical procedures to make them less invasive, reduce the training time for the next generation of surgeons, reduce surgical errors, and improve patient safety on a global scale. 

REFERENCES