Challenges in Robotics and Simulation for Minimally Invasive Surgery: Proposal for the NSF/CCC/CRA Roadmapping Workshop for Medical and Healthcare Robotics

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Traditional surgery requires an incision large enough for the surgeon to see directly and place his or her fingers and instruments directly into the target operating site. Most often, the damage done to skin, muscle, connective tissue, and bone to reach the region of interest causes much greater injury than the curative procedure itself. This results in more pain to the patient, longer recovery times, and complications due to surgical trauma. The accelerating trend is toward minimally invasive surgery (MIS), in which unnecessary trauma is limited by reducing the size of incisions to 1 cm or less or eliminating external incisions by working through natural orifices. The other side of MIS, unfortunately, is that from the surgeon's point of view it is minimal access surgery. Reduced access reduces dexterity, limits perception, increases strain and the likelihood of error, and lengthens procedure time.

Teleoperation technology can restore some of the lost dexterity and sensation. The surgeon uses master controllers to command the slave manipulator position, while interaction forces between the slave and tissue are reflected to the master. It is then possible to design the master to provide a good interface to the properties of the surgeon's hand, such as range of motion and perceptual capabilities, while optimizing the slave manipulator to the properties of tissues, to allow maximal control and sensation with minimal trauma. Control algorithms can be designed to shape the mechanical impedance characteristics of the teleoperator. Similar technology could be used in remote surgery for experts to perform or assist surgery in remote rural areas, or for emergency care in urban trauma or the battlefield. However, current systems are still bulky and have poor force feedback.

Society demands greater efficiency in medicine as costs have soared. New technologies, however, are often less efficient than the methods they replace. Minimally invasive surgical techniques, for example, are often slower than conventional procedures because of the greater demands they place on human perceptual-motor abilities. Across the spectrum of medical care there is more to learn, while resident work hours have been reduced and practicing physicians have less time for continuing education. Physicians no longer interact directly with the patient and surgeons do not handle tissue directly. Instead there is an interface providing information and, in interventional procedures, extending the clinician's reach through minimally invasive devices.

Access. Advanced robotics technologies can offer the possibility of reaching regions of the body that are currently inaccessible by minimally invasive techniques while achieving high levels of dexterity and sensation. These include intracardial and pericardial spaces, endoscopy of the gastrointestinal tract, neurosurgery, pediatric and fetal surgery, and natural orifice transluminal endoscopic surgery (NOTES). New approaches to millimeter-scale robotics are needed to achieve the potential of minimally invasive surgery. These include novel approaches to kinematics and mechanical design such as parallel kinematic designs with flexural joints. Advanced integrated sensors can provide a wealth of information to the surgeon, including improved force feedback, and enable tracking to compensate for heart or breathing motion. Real time imaging of actuated devices will enable new procedures and make current procedures safer. Because forces of several Newtons or more are often need to be applied, advanced microactuator technologies such as electroactive polymers could enable robots capable of working inside the body with minimal tethering to the outside.

Better interfaces. With current technology, robotic surgery feels different from open surgery, which is quite different from minimally invasive surgery, and simulated procedures often fail to behave realistically like any of these. Surgeons comfortable with performing a procedure often struggle when it is necessary to do the same procedure using a different modality.

Although one might assume that touch is essential to skillful surgery, current surgical interfaces, including minimally invasive techniques, robotic systems, and simulation, have poor or no haptic feedback. The mechanics of laparoscopic instruments and friction from cannulas reduce kinesthetic feedback. Commercial robotic surgical systems that have been developed have very limited or no force feedback. Although some commercial simulators for surgical training offer haptic feedback, the underlying mechanical models are very crude and do not behave realistically.

Surgeons can compensate for poor haptics because vision is often better in minimally invasive than in open surgery because the scope can be placed very close to the operative site. The surgeon views a highly magnified image, produced by an imaging system with high resolution and excellent color quality. Problems arise, however, when the surgeon cannot see because of bleeding, adhesions (due to infection or a previous operation), or fat. These are indications for conversion from laparoscopic to an open operation, and proceeding under poor visual conditions often leads to complications. However, many procedures are so commonly done laparoscopically that surgeons are unpracticed in performing them using open techniques.

Ideally, the surgical interface should be as similar as possible so that performing a simulated procedure is like doing the real thing and the procedure is nearly the same whether performed open, laparoscopically, or robotically. The challenges are, first, to understand the requirements of minimally invasive procedures and the human limitations of the surgeon. Through a combination of robotics, interface design, improved training through simulation, and automation, the ultimate goal is to make surgical performance as consistent as possible across modalities so that the surgeon's experience can be applied no matter how the procedure is performed or practiced.

Training in Simulation. Training in surgery has been principally based on an apprenticeship model. Residents learn by watching and participating, taking more active roles in the operation as their experience increases. This model has endured in part because the techniques of traditional open surgery mostly rely on familiar eye-hand coordination and most residents could achieve competence by repeated practice. With the introduction of new minimally invasive techniques, perceptual-motor relationships are unfamiliar and the learning curve is steep. The other major reason for the survival of apprenticeship is the inadequacy of alternatives such as cadavers, live animals, and in vitro training models made of synthetic materials. Virtual environments (or virtual reality) have great promise for surgical training.

The most fundamental technical challenge in surgical simulation is modeling and rendering the behavior of tissue realistically at computational speeds adequate for smooth visual and haptic interaction. The fundamental research issues are the modeling of tissues and interactions, haptic rendering of these interactions, development of effective haptic interfaces, and development of training methods utilizing virtual fixtures and haptic guidance. These are all areas where the robotics community needs to play a significant role.