Observation, Manipulation, and Eye-Hand Coordination Problems in Minimally Invasive Surgery

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Abstract

Laparoscopic surgery is a minimally invasive method of surgery which is performed by using an endoscopic camera and long and slender instruments that are inserted through small incisions in the skin of the patient's abdomen. The surgeon performs the operation indirectly by manipulating the instruments and observing the camera pictures on a monitor. The advantage of this new technique is that it reduces the damage of the body and in principle also the risk of infection and the recovery time. Disadvantages are that it causes the surgeon to have observation, manipulation and eye-hand coordination problems. This paper describes a mental model of the surgeon's activities and it gives an overview on the observation, manipulation and eye-hand coordination problems in this new area of manual control.

Introduction

Endoscopic surgery is a minimally invasive method of surgery which is performed by using an endoscope and long and slender instruments that are inserted through small incisions in the skin. The surgeon carries out the surgery without direct contact with the organs. He/she performs the operation indirectly by spatially manipulating the instruments and by observing the operative scene through the endoscope, either under *direct vision* by using an ocular, or under *indirect vision* by using an endoscopic camera. The camera pictures are displayed on a monitor.

Endoscopic surgery is called *laparascopic surgery* when the operation is carried out in the patient's *abdomen*. The surgeon uses one or two laparoscopic instruments to carry out the operation. The endoscope, which is held by a *camera assistant*, is equipped with a camera that shows a view on the operative scene. The camera picture is displayed on one or two monitors in the operation room. In order to create a workspace for the instruments and the endoscope, the patient's abdomen is inflated with carbon dioxide. The endoscope and the instruments have a diameter between 5 and 12 mm. They are inserted through *trocars*. These are tubes that are placed in the incisions in the abdominal wall. The trocars provide an airtight seal between the instrument and the skin and they protect the skin against damage. Detailed information about laparoscopic operations can be found in Cuschieri [1992].

Compared with conventional open abdominal surgery which is carried out through a large incision in the skin, the advantages of laparoscopic surgery are that it reduces the damage of the body and in principle also the risk of infection and the recovery time. Laparoscopic surgery techniques are therefore more and more frequently used. Disadvantages are that the operation protocols are still far from optimal and that it is difficult for the surgeon to map pre-operative information from X-ray, Ultrasound or MRI images onto the endoscopic camera pictures. Other difficulties concern the indirect way of observing and manipulating. They cause the surgeon to have *observation, manipulation* and *eye-hand coordination problems.*

In order to find solutions for these problems, a research program on minimally invasive surgery techniques was initiated at the Delft University of Technology in cooperation with the Academic Medical Centre in Amsterdam and several other hospitals in the Netherlands. The program is called MISIT, which is short for Minimally Invasive Surgery and Intervention Techniques. The program consists of six projects, varying from pre- and peroperative evaluation of the surgical process to miniaturisation of sensors for use in catheters.

This paper describes the results of a problem analysis of a MISIT project that focuses on eye-hand coordination and telemanipulation. Section 0 describes a mental model of the surgeon's observation and manipulation activities, and Sections 0, 0 and 0 give an overview of the observation, manipulation and eye-hand coordination problems. Section 0 ends with the conclusions.

A mental model of the surgeon's observation and manipulation activities

Observation and manipulation activities during open abdominal surgery

In order to get more insight in the eye-hand coordination problems of the surgeon, a mental model of the surgeon's observation and manipulation activities was developed.

Figure 1 shows the model in the case of *open abdominal* surgery. The model only describes the surgeon's activities during *free movement.* Tactile feedback in contact situations with the organs was not included to keep the model simple.

The surgeon observes the operative area and his/her hands that are manipulating the instruments. The picture of the operative scene is projected on the retina, and transformed into a set of visual signals that are sent to the retinal cortex.

The retinal cortex uses two filters to extract the required information from the visual signals: a *static environment filter* and a *dynamic movement filter.* The output of the static environment filter is a visual image of the operative area, and the output of the dynamic movement filter is a visual measurement of the hand movements. *A hand movement planner* uses the visual image of the operative area to determine which desired hand movements are required to perform the task. A *visual hand controller* compares the desired hand movements with the visual measurement. It generates a correction signal when the two signals differ from each other.

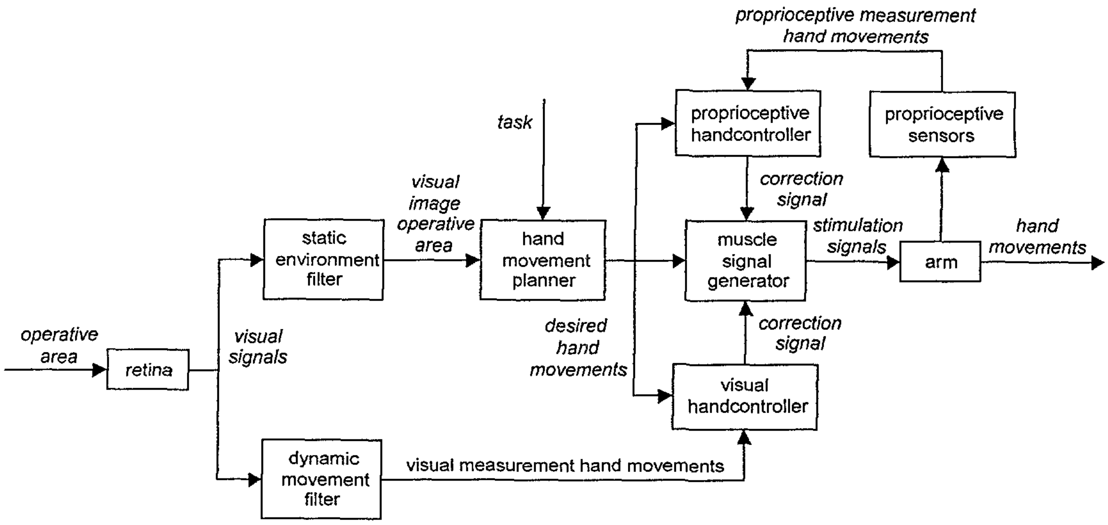

Figure 1: Mental model of the surgeon's observation and manipulation activities during *open abdominal* surgery.

Besides the visual information coming from the eye, also *proprioceptive sensors* give information about the position of the arms and the hands of the surgeon. The muscles contain *muscle spindles* that measure the muscle's length and velocity, and the tendons contain *Golgi tendon organs* that measure the muscle force. The proprioceptive sensors in the surgeon's arms produce a proprioceptive measurement of the hand movements. A *proprioceptive hand controller* compares the desired hand movements with the proprioceptive measurement. It generates a correction signal when the two signals differ from each other.

The desired hand movements and the two correction signals are inputs of a *muscle signal generator* that generates stimulation signals for the muscles in the upper- and forearms of the surgeon. The contractions of these muscles result in the hand movements that are needed to perform the task.

Observation and manipulation activities during laparoscopic surgery

Figure 2 shows the mental model during *laparoscopic* surgery. The surgeon observes the operative scene indirectly by means of a monitor and an endoscopic camera that is inserted through a small incision in the skin. This results in an extra transformation at the observation side of the model. The surgeon manipulates the instruments indirectly through long and slender shafts that are also inserted through small incisions in the skin. This results in an extra transformation at the manipulation side of the model.

The indirect way of observing hampers the surgeon in the observation activities and is a source of *observation problems*. The indirect way of manipulating hampers the surgeon in the manipulation activities and is a source of *manipulation problems*. The combination of indirect observation and indirect manipulation results in discrepancies between visual instrument movements and expected instrument movements. This results in the surgeon to have *eye-hand coordination problems*.

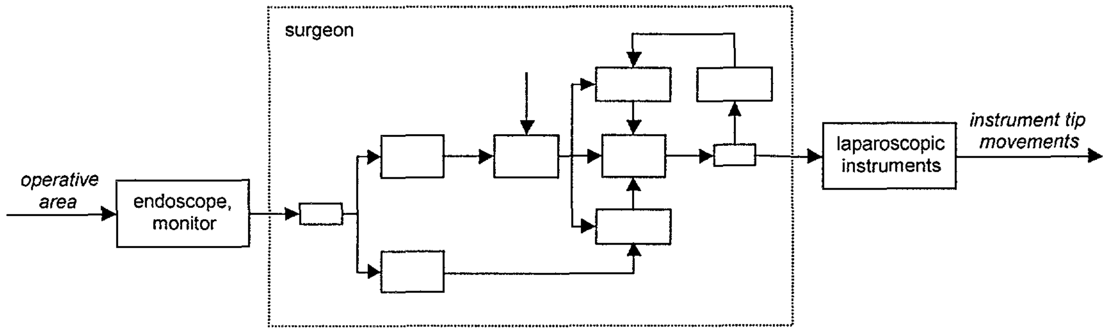

Figure 2: Mental model of the surgeon's observation and manipulation activities during *laparoscopic* surgery.

Observation problems

Introduction

The observation problems can be subdivided into three groups: Problems concerning the *collection* of the visual information, problems concerning the *nature* of the visual information, and problems concerning the *perception* of the visual information, Table 1. gives an overview of the problems in these groups.

Collection of the visual information

It is common in laparoscopic operations that the surgeon is not directly in control of the endoscope. The visual information is collected by a camera assistant who controls the endoscope by listening to the surgeon's instructions and by using a set of empirical rules to position the endoscope [Danis 1996]. This indirect way of adjusting the viewpoint is not very intuitive. It can lead to communication problems between the surgeon and the assistant, and to an unsteady camera picture when the assistant has to maintain a fixed pose for a long time.

Nature of the visual information

In the case of open abdominal surgery, the surgeon looks down on the patient's abdomen, observing a *top view of a large part of the operative area.* In the case of laparoscopic surgery, however, the surgeon looks forward to the monitor, observing an *enlarged side view of a small part of the operative area.* The nature of the visible information thus differs from what the surgeon is used to in open surgery. The endoscope shows a *magnified picture* of the operative area, with a *different line-of-sight* and with a *small field-of-view.*

A positive effect of the magnified view is that the picture of the operative scene is larger and more detailed. Hence, small anatomic structures are more easy to discern [Cuschieri 1992]. A positive effect of the different line-of-sight is that it can be more convenient for some operations.

Negative effects of the magnification, the different line-of-sight, and the small field-of-view are that it becomes more difficult to find and to identify anatomic structures [Cuschieri 1992, Champion et al. 1996]. The small field-of-view leads to frequent

Table 1: Observation problems in conventional laparoscopic surgery.

Observation problems in laparoscopic surgery
1. Collection of the visual information Indirect viewpoint adjustment by a camera assistant
2. Nature of the visible information Finding & identifying anatomic structures Frequent endoscope manoeuvres required
3. Perception of the visual information General perception problems Reduced resolution, contrast & illumination Dirt & vapour on the endoscope lens Depth perception problems No shadows in the endoscopic camera pictures No stereovision No movement parallax Misfits of accommodation & convergence

endoscope manoeuvres, e.g. to move the endoscope lens to the abdominal entry point of a newly inserted instrument. Such manoeuvres are not only inconvenient and time-consuming, but they can also lead to potentially dangerous situations, e.g. when instruments not in sight injure structures in the operative area [Champion et al. 1996, Schippers & Schumpelick 1996].

Perception of the visual information

General perception problems

Besides problems with the collection and the nature of the visual information, the use of a camera and a monitor can also cause problems with *visual perception.* A potential cause for general visual perception problems is the *quality* of the picture on the monitor. The picture quality is strongly influenced by the camera and monitor properties and by dirt and vapour on the endoscope lens [Cuschieri 1996, Schippers & Schumpelick 1996]. The quality of modern rigid endoscopes is usually very good. The quality of flexible endoscopes and stereo-endoscopes, however, is usually less good due to the use of glass-fibers and a double lens system within the same endoscope diameter. Dirt and vapour on the lens is a frequent and irritating event that requires the surgeon to interrupt the operation for cleaning.

Depth perception problems

An important topic of visual perception is *depth perception*: the estimation of distances and movements *perpendicular* to the image on the retina. A human can use three depth information sources to estimate such distances and movements: *pictorial information*, *parallax*, and *visuomotor cues* [Regan et al. 1979, Cuschieri 1996, Sheridan 1996]. The visual cortex uses a set of empirical rules to transform the information from these sources into the information which is required to perform a spatial manipulation task or to analyse the situation:

1. *Pictorial information* concerns the pictorial cues in the retinal image that give information about distances and movements perpendicular to that image. Examples of such cues are: 'an object that overlaps another object is closer to the observer' and 'an object touches a surface when it touches its shadow on the surface'. The last cue is very helpful for fine positioning tasks.

2. *Parallax* concerns changes in the mutual positions of objects in the retinal image when the viewpoint of the eye changes. Two kinds of parallax can be distinguished: *binocular disparity* and *movement parallax. Binocular disparity* concerns the disparity between the two pictures seen by the left eye and the right eye caused by the distance between the two eyes. Objects with a different distance to the observer are shifted with respect to each other in the two pictures. The size of the shift gives information about their spatial position. *Movement parallax* concerns shifts in the picture seen by one eye when the head of the observer moves. The head movement causes the visible objects to shift with respect to each other, and also this shift gives information about their spatial position. In the literature, also the term *motion parallax* is used. Motion parallax refers to a shift in the retinal image not caused by the observer's head movement, but by an external influence. A well known example of motion parallax occurs when the observer watches a movie. Shifts in the retinal image are then not caused by the observer's head movement, but by the movement of the camera.

3. *Visuomotor cues* concern the movements of the eyeballs and the eyelenses to focus an object. Visuomotor cues can be subdivided in two kinds: *accomodation* and *convergence*. Accomodation is the adjustment of the eyelens to focus on an object. Convergence is the horizontal and inward rotation of the eyes to point them to the object.

In normal life, the observer can use all the depth information sources mentioned above to perform a spatial manipulation task. In the case of laparoscopic surgery, however, the use of the depth information sources is limited. This results in difficulties and mistakes in the estimation of spatial distances and movements in the endoscopic camera pictures:

1. In all standard endoscopes, the light source is located at the tip, forming a ring of light around the lens. This is advantageous for the brightness of the endoscopic camera pictures, but disadvantageous for the surgeon's depth perception, since the endoscopic camera pictures contain in principle no shadows. This makes it more difficult for the surgeon to spatially position the laparoscopic instruments accurately [Schippers & Schumpelick 1996].

2. Conventional endoscopes are monocular and controlled by a camera assistant. The surgeon is thus not able to use binocular disparity and movement parallax as depth information sources. When the assistant moves the endoscope, motion parallax is present to some extent, but the amount of information is limited. The incision point of the endoscope acts like a spherical joint that restricts the number of endoscope degrees of freedom (DOFs) from six to four. As a result, it is impossible to keep the viewpoint in focus and to 'look around a corner'. Many

Table 2: Manipulation problems in conventional laparoscopic surgery.

Manipulation problems in laparoscopic surgery
1. Transformation of spatial movements of the hand Restriction in DOFs from 6 to 4 Mirroring of the hand movements & the tip forces Scaling of the hand movements & the tip forces Friction along the instrument shaft
2. Transformation of grasping movements of the hand Difference in size between grasper & hand Difference in grip between grasper & hand Poor tactile feedback Bad ergonomic handgrip design

laparoscopic surgeons experience this as a handicap [Cuschieri 1995, Treat 1996].

3. When the surgeon looks at the endoscopic camera pictures on the monitor, the eyelenses focus on the surface of the television screen, and not at the visible objects 'behind' the screen. This makes the information coming from visuomotor cues useless for depth perception.

These effects hinder the surgeon in the execution of the task and require the surgeon to adapt him/herself to the limitations of the indirect way of observing.

Manipulation problems

Introduction

The manipulation problems can be subdivided into two groups: transformation of *spatial movements* from the surgeons hand to the instrument tip, and transformation of *grasping movements* from the surgeon's hand to the grasper on the tip, Table 2. Sections 0 and 0 give an overview of the problems in these groups. Problems in the last group are of course only present when the laparoscopic instrument contains a tip with moving parts, like a grasper or a pair of scissors. An example of an instrument with a grasper is a laparoscopic grasping forceps. An example of an instrument without moving parts is a laparoscopic dissecting hook. An overview of laparoscopic instruments can be found in Melzer et al. [1996].

Transformation of spatial movements of the hand

The spatial movements of the surgeon's hand are transmitted via the instrument shaft through the incision point into spatial movement of the instrument tip. This indirect way of manipulating the instrument tip results in a number of effects:

The incision point of the instrument acts like a spherical joint that *reduces* the number of DOFs of the tip from six to four. This makes it impossible to move the instrument tip around a corner to approach the anatomic structure from aside. Many laparoscopic surgeons experience this restriction as a large handicap [Cuschieri 1994, Treat 1996]. The restriction of the instrument movements and the fixed location of the incision points forces the surgeon often to uncomfortable poses to reach the anatomic structure of concern with the instrument tip. This causes the surgeon to become tired.

Another effect of the incision point is that it *mirrors* the hand movements. This means, e.g. that when the surgeon moves his/her hand to the *right*, the instrument tip in the patient's abdomen moves to the *left* [Treat 1996]. Besides mirroring the hand movements, the incision point also mirrors the tipforces when the instrument tip touches an anatomic structure, so that the contact force on the surgeon's hand points in the opposite direction.

A third effect of the incision point is that it makes the shaft of the instrument act like a lever that amplifies or reduces the surgeon's hand movement, depending on the location of the incision point along the shaft. This introduces a variable *scaling* factor between the movement of the surgeon's hand and the movement of the tip [Treat 1996]. The incision point and the shaft also scale the tipforces when the instrument tip touches an anatomic structure, so that the magnitude of the contact force on the surgeon's hand differs from the tipforce.

In order to create a workspace, the patient's abdomen is inflated with carbon dioxide. The trocars through which the endoscope and the instruments are inserted are *airtight* so that no carbon dioxide can disappear. The airtight seal results in *friction* between the instrument shaft and the trocar. The friction works against the instrument movement when the surgeon wants to move it perpendicular to the abdominal wall.

These effects hinder the surgeon in the execution of the task and require the surgeon to adapt him/herself to the differences and restrictions coming from distant manipulation via long shafts through small and airtight incisions.

Transformation of grasping movements of the hand

The grasper of a laparoscopic grasping forceps consists of two jaws. The grasping movements of the surgeon's hand are transmitted through the instrument shaft into opening and closing movements of the jaws. This indirect way of grasping anatomic structures results in a number of effects:

The grasper of the forceps is much smaller than the surgeon's hand. This *difference in size* makes it more difficult to grip larger anatomic structures, e.g. to lift the gallbladder in a laparoscopic cholecystectomy. In conventional open surgery, the surgeon would just place his/her hand under the bladder to lift it up. The small size of the laparoscopic grasper, however, makes this more complicated since the bladder will easily slip off the grasper. This problem can be solved by grasping the gallbladder from above, but this incorporates risk of damage due to large contact forces between the jaws and the gallbladder skin.

The grasper of the forceps consists of only two rigid yaws with 1 DOF. As a result, only the *magnitude of the grip* and *the average force on the jaws* can be adjusted. The surgeon's hand, however, consists of 27 bones with more than 20 DOFs. This makes it possible to adjust the *magnitude of the grip*, the *force distribution over the palm and the fingers* and the *shape of the grip*. This *difference in grip* makes the surgeon's hand much more suitable to grasp a wide variety of objects with different shape and fragility [Cuschieri 1994, 1996].

The grasping mechanism of conventional laparoscopic instruments suffers from backlash and friction due to the airtight construction. As a result, there is a very *poor tactile feedback* of contact forces from the jaws to the surgeon's hand [Cuschieri 1994, 1996, Fischer et al. 1995, Schippers & Schumpelick 1996]. If the grasping mechanism would be frictionless, the surgeon would only be able to detect the *average force on the jaws,* scaled by the grasping mechanism and the handgrip. The surgeon's hand, however, is able to detect not only the *force distribution over the palm and the fingers*, but also the *temperature* and the *surface structure* of the organ. This gives the surgeon much more tactile information.

The handgrips of many laparoscopic instruments suffer from a *bad ergonomic design.* The inadequate fit of the handgrip to the properties of the human hand results e.g. in too large forces and too small hand finger movements to move the grasper. For the surgeon, this leads to fatigue or cramp in his/her hands.

These effects hinder the surgeon in the execution of the task and require him/her to find alternative ways to perform the task correctly in spite of the restrictions and imperfections of his instruments. The effects are equivalent when the laparoscopic instrument contains a pair of scissors instead of a grasper.

Eye-hand coordination problems

Introduction

The outputs of the hand movement planner and the visual hand controller in Figure 1 and Figure 2 are desired hand movements with respect to the *retinal image* of the operative area. The muscle signal generator transforms these signals into stimulation signals for the muscles in the upper- and forearms of the surgeon. The signals are generated by an *internal model* that describes which muscles have to be stimulated and how far they have to contract to realize the desired hand movement with respect to the retinal image. The internal model has been constructed and improved after years of every day life training and experience in normal situations like in open abdominal surgery, when the surgeon observes and manipulates the surgical instruments *directly*. In the case of laparoscopic surgery, however, the situation is unnatural due to the *indirect* way of observing and manipulating. This leads to confusing discrepancies between the internal model and the real situation causing the surgeon to have *eye-hand coordination problems* [Cuschieri 1994, 1995, Wade 1996], Table 3.

Location of the visual scene

The first effect that can lead to confusion is the *location of* the visible scene. In the case of *open* abdominal surgery, the surgeon looks *downward* to the operative area and on his/her hands that are manipulating the instruments. In the case of *laparoscopic* surgery, however, the surgeon looks *forward* or *sideward* to the endoscopic camera pictures on the monitor. The location of the visual scene is thus *decoupled* from the location of the actual operative area. This is unnatural.

Table 3: Eye hand coordination problems in conventional laparoscopic surgery.

Eye-hand coordination problems in laparoscopic surgery
1. Location of the visual scene • Surgeon looks at monitor and not at actual operative area
2. Effects in the visual scene Amplification of the hand movements Mirroring of the hand movements Misorientation of the hand movements

Effects in the visual scene

Several *effects in* the visual scene lead to discrepancies of the internal model and the real situation. When being introduced to the laparoscopic surgery technique, a resident surgeon identifies the tips of the laparoscopic instruments on the monitor with his/her hands. When the resident uses the internal model for normal situations to determine the muscle stimulation signals, however, he/she notices that the instrument tips on the monitor do not react according to the expectation. This is caused by a number of effects:

The endoscope and the monitor show a magnified view on the laparoscopic instruments. The size of the magnification depends on the size of the monitor, the lens properties of the endoscope, and the distance from the endoscope lens to the instrument tips. Furthermore, the shaft of each instrument acts like a lever that amplifies or reduces the surgeon's hand movement. These effects introduce a variable *amplification* between the surgeon's hand movements and the movements of the instrument tips in the camera picture. Consequently, the instrument tips in the retinal image move faster than expected from the internal model. The surgeon has to compensate this effect by scaling the hand movements mentally. A similar effect occurs in Window-based software when the mouse gain is increased. This results in a sudden and confusing increase in cursor speed.

The instrument incision points *mirror* the surgeon's hand movements, so that that the instrument tip moves to the *left* in the camera picture when the surgeon moves his hand to the *right.* The instrument tips thus move in an opposite direction than expected from the internal model. The surgeon has to compensate this effect by mirroring the hand movements mentally. A similar effect occurs in Window-based software when the mouse is rotated 180 degrees so that the cursor movement is reversed. Left/right mouse movements then result in right/left cursor movements. This is confusing.

The endoscope, which is controlled by a camera assistant, is inserted into the abdominal wall at a location and at an angle where it doesn't hamper the surgeon and the operation team in their activities. As a result, the line-of-sight of the endoscopic camera is usually different from the natural line-of-sight the surgeon would have when he/she could look directly on the scene. Since the endoscopic camera pictures show a rotated view on the scene, the instrument tips in the retinal image move in a different direction than expected from the internal model. The surgeon has to compensate this *misorientation* by rotating the hand movements mentally [Kim et al.

1987, Boer 1991, Pichler et al. 1997]. An effect similar to a 90 degrees misorientation in the endoscopic camera picture occurs in Window-based software when the mouse is rotated 90 degrees. Left/right mouse movements then result in up/down cursor movements. This is very confusing.

The surgeon has to compensate these effects by adapting the internal model to laparoscopic situations. This is achieved by an intensive and time-consuming training period during the stage as a resident and during his/her practice as a laparoscopic surgeon.

Conclusions

Table 1, Table 2 and Table 3 give an overview on the observation, manipulation and eye-hand coordination problems of the surgeon in *conventional* laparoscopic surgery where the endoscope is monocular and controlled by a camera assistant, and where conventional laparoscopic instruments are used. The problems are most confusing for a resident surgeon who is not used to the laparoscopic technique.

Some problems, like the mirroring and scaling of the hand movements and the tip forces, and the friction along the instrument shaft, are small and easy to get used to. Other problems, like the depth perception problems and the eye-hand coordination problems, are larger. They require an intensive and time-consuming training period in which the surgeon adapts his/her internal models for observation and manipulation in everyday life to laparoscopic situations. Problems like the reduction in instrument DOFs from 6 to 4, the difference in size and grip between grasper and hand, and the poor tactile feedback, however, will remain present even after a long training period with conventional laparoscopic instruments. They require the surgeon to find alternative ways to perform the task correctly.

In the minimally invasive literature, a number of possible solutions for the problems have been found. An overview can be found in Breedveld [1998]. Examples of solutions are automatic endoscope positioners that are directly in control of the surgeon [Sackier & Wang 1994, Finlay & Ornstein 1995], endoscope irrigation systems that remove blood and vapour from the lens [Schurr et al. 1996], stereo-endoscopes that project a stereo image of the operative scene on two television screens in front of the surgeon's eyes [Geis 1996], instruments with movable tips that restore the decrease in DOFs [Schurr et al. 1993], and instruments with almost no friction that improve the feedback of tactile information [Herder et al. 1997]. Most solutions focus on *only one* of the problems mentioned in the tables. *Integrated* solutions that solve a large number of problems at the same time are rare. Some solutions are already commercially available, but most of them are still in the research phase. General disadvantages are that they make the equipment more complex, resulting in larger chance on failure, difficulties with sterilizing, and large purchasing costs for hospitals. The quest for a simple and adequate solution for the problems is therefore still an important topic of research in this new area of manual control.

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