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TASK AND MOTION ANALYSES IN ENDOSCOPIC SURGERY

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ABSTRACT

We present here task and motion analyses, part of a larger study on users, tasks and tools in endoscopic surgery. Expert and novice surgeons' performance of laparoscopic surgery in training workshops was captured on video and analyzed. Four basic surgical tasks were identified: dissecting tissue, suturing, tying knots, and cutting suture. Each task was decomposed into subtasks with operational beginnings and endings. Subtasks were further analyzed into component motions. Here we discuss: differences between novice and expert surgeons; task constraints that might account for the pattern of results across the different tasks, including precision and safety constraints; differences in manipulation of the same endoscopic tool as a function of the target object; the large number of “additional” motions; difficulties in positioning and orientation of tools to perform the surgical tasks; and the serial execution of reach and grasp movements in endoscopic surgery, compared to their parallel execution in natural prehension.

1. INTRODUCTION

Endoscopic surgery, or minimally invasive surgery, requires surgeons to operate by remote manipulation, using specially designed endoscopic tools. In laparoscopic surgery, which includes most general procedures performed in the abdomen, these tools are inserted into the patient’s abdominal cavity through small incisions in the abdominal wall. Entire surgical procedures are performed by manipulating the tool handles from outside the patient’s body, without direct contact with the diseased tissue, and without direct vision of the operative site. The remote operative field is viewed by an endoscope, also inserted into the abdominal cavity through an incision in the abdominal wall. The endoscopic view of the operative site is captured by a miniature camera in the endoscope and displayed on a 2-D video monitor for the operating surgeons.

Empirically, little is known about human performance in endoscopic surgery, or the task requirements and constraints. Compared to open surgery, endoscopic performance of surgical tasks is affected by additional physical, visual, motor, spatial, and haptic constraints. The very tools which allow surgical operations to be performed with minimal invasiveness are themselves a major physical constraint (see Fig. 1). Part of a larger exploratory study on the users, tasks and tools in endoscopic surgery, this paper reports on preliminary task and motion analyses, with a surgeon-centred focus on manipulation in performance of surgical tasks. Human manipulation necessarily includes both free motion and compliant motion (force-applying) phases. Our exploratory analysis includes both phases, through measures of time spent and the number of attempts to accomplish the surgical task and subtask goals.

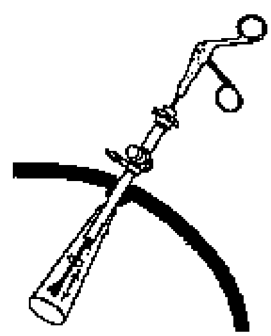

Figure 1. Degrees of freedom (DOF) of a conventional instrument in endoscopic surgery (from Melzer et al., 1992, p.15). Excluding the end-effectors, there are 4 DOF: 1) translation along the shaft of the tool, 2) rotation around the translational axis, 3 & 4) limited incline of the shaft pivoted in the abdominal wall.

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2. METHOD

Four laparoscopic training workshops were videotaped. One expert (teaching surgeon) and five novice (residents) surgeons' performance in laparoscopic surgery on anaesthetized pigs was captured on video. A video camera was set up to record the surgeons' hand movements, with the image of the operative site from the endoscopic camera, including end-effectors of the manipulators, recorded on the same videotape in a split-screen fashion. A Panasonic Digital AV Mixer with a picture-in-picture feature was used (see Fig. 2). Videotapes were recorded at the standard play speed (SP) on a Sony VCR.

Task and motion analyses were based on the videotape segments during which the endoscopic camera had a fixed point of view. Videotape analysis was performed using Timelines (Harrison, Owen, & Baecker, 1994), a computerized video annotating and coding system. Four basic surgical tasks which used endoscopic manipulators were identified: dissecting tissue, suturing, tying knots, and cutting suture. Each task was decomposed into subtasks with operational beginnings, endings and target states. Each of the subtasks was further analyzed into component motions, using Timelines. The four tasks and expert and novice surgeons were compared on: the time taken to complete each task and subtask, the component motions and the number of attempts for each of the component motions to achieve the task goals. The number of trials by each surgeon in each of the tasks were not constant. Thus, for novice surgeons, the mean duration of each subtask was averaged over the total number of trials, and an average within subject variability reported. An average timeline was then created for each task. Motion analysis was limited to a qualitative description of the end-effector's movement characteristics and a simple scoring of the number of repeated attempts made by the surgeons.

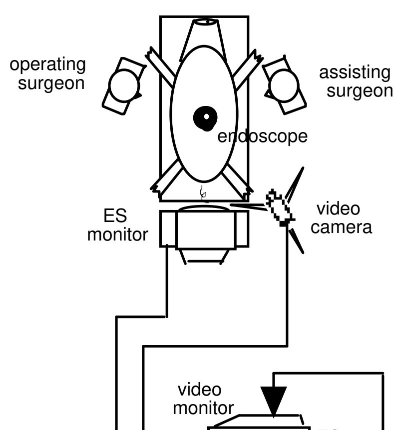

Figure 2. Layout of operating room and video camera position in the workshops. Signals from the video camera and endoscopic system monitor feed into the mixer and display on the monitor as one picture set in the other. The VCR records the 2 pictures as one image onto a VHS tape.

3. RESULTS

3.1 Task Analysis

Based on the operational definitions of subtasks (Table 1), timelines were constructed for suturing, tying knots, cutting suture and dissecting tissue (Fig. 3, 4, and 5, respectively), for both the teaching surgeon (expert), and the training surgeons (novice). Task analysis revealed that suturing is the longest and most involved of the four basic surgical tasks, followed by tying knots, dissecting tissue, and cutting suture. In general, novice surgeons spent more time in each subtask, and consequently in each task, than the expert surgeon.

For suturing (Fig. 3), seven subtasks were identified. While the average time spent in most subtasks was twice as long for the novice surgeons, the most notable differences in mean duration between the expert and the novices were in the needle positioning subtasks. For the first positioning subtask in suturing, the expert surgeon spent, on average (n=7), 51 seconds orienting the needle such that it was poised to be passed through the tissue. The four novice surgeons spent an average (n=10) of 103 seconds doing the same.

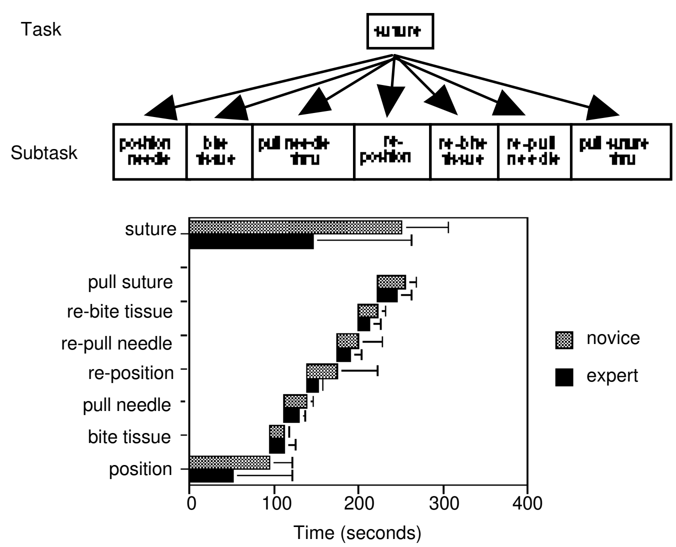

Figure 3. Timeline for suturing.
Top: Suturing is decomposed into seven subtasks: 1) position needle, 2) bite tissue, 3) pull needle through, 4) re-position needle, 5) re-bite tissue, 6) pull needle through, and 7) pull suture through tissue.
Bottom: The timeline compares the average times spent in each subtask for an expert surgeon (n=7), and for five novice surgeons (n=10). The error bars represent within subject variabilities. For the novice surgeons, the variability was an average of the within subject variabilities of three surgeons who performed more than one trial of each subtask.

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Table 1. Operational definition of subtask initiation and termination for timeline analysis.

Task	Subtasks	Tool	Begin	End
Suture	1. position needle	1 needle driver, 1 needle holder	first movement of needle driver toward the needle or suture	contact of needle with tissue
	2. bite tissue	1 needle driver, 1 needle holder	contact of needle with tissue; end of position and orient needle	emergence of tip of needle on other side of tissue
	3. pull needle through	1 needle holder, 1 needle driver	first movement of needle holder toward tip of needle	end of first pulling movement with needle through tissue
	4. re-position needle	1 needle driver, 1 needle holder	first movement of needle driver toward the needle or suture	contact of needle with tissue
	5. re-bite tissue	1 needle driver, 1 needle holder	contact of needle with tissue; end of position and orient needle	emergence of tip of needle on other side of tissue
	6. re-pull needle through	1 needle holder, 1 needle driver	first movement of needle holder toward tip of needle	end of pulling movement with needle through tissue
	7. pull suture through	1 needle driver, 1 needle holder	first movement of needle driver/holder toward suture	release of suture after adjusting for appropriate length
Tie knot	1. position needle and suture	1 needle driver, 1 needle holder	first movement of needle driver toward the needle or suture	needle holder is in position to have suture loop around it; begin of loop
	2. form loops	1 needle driver, 1 needle holder	first movement of driver with needle and suture in grasp, to loop around holder	completion of loops; before begin of pull through
	3. pull short tail through loops	1 needle driver, 1 needle holder	end of loop; first movement of holder toward short tail of suture	tail of suture pulled through loops
	4. pull knot tight	1 needle driver, 1 needle holder	first movement of needle driver toward the needle or suture	release of suture after tightening knot
Cut suture	1. pull taut suture	1 graspers	first movement of the graspers toward suture to be cut	termination of pulling movement; suture taut
	2. snip suture	1 scissors	first movement of scissors toward suture	closure of scissors jaws; successful separation of suture
Dissect tissue	1. pull taut tissue	1 graspers	first movement of the graspers toward tissue to be cut	termination of pulling movement; tissue taut
	2. snip tissue	1 scissors	first movement of scissors toward tissue	closure of scissors jaws; successful separation of tissue

In the subsequent positioning subtask to put in the second stitch, which is a repeat of the first, the differences are more remarkable. The novice surgeons reduced the duration of the second positioning subtask by over one-half (42 seconds); the expert surgeon was able to reduce it by one-fourth (12 seconds). A major difference between the expert and novice surgeons seemed to lie in proficiency at grasping the needle and moving it to a desired position and orientation, without slipping or dropping it. For the expert, the needle coming out the first bite of tissue was in a position and orientation very close to that desired, such that less time was required to manipulate it.

Similarly for tying knots, a large portion of time was spent in positioning (see Fig. 4). The expert surgeon spent, on average, 16 seconds (n=15) in this subtask. The novice surgeons, on the other hand, spent about twice as long (31 seconds, n=23) positioning. This was true for all but the last subtask, pulling knot tight. The surgeons spent approximately the same time pulling the knot tight (17 seconds for expert, and 19 seconds for novices). The disproportionate time difference between the two groups of surgeons seemed to be a reflection of the requirements and constraints of the subtasks. The novice surgeons slowed down in three of the four subtasks for which accuracy in positioning required some degree of orientation.

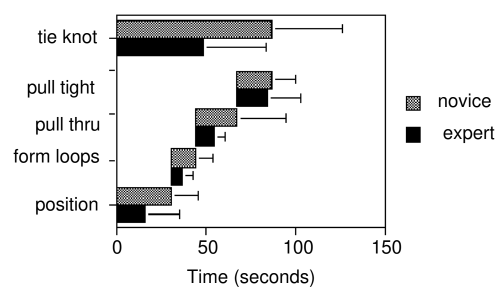

Figure 4. Timeline for tying knots. The timeline compares the average times spent in each subtask for an expert surgeon (n=15) and five novice surgeons (n=23) who were learning the laparoscopic technique in the workshops. The error bars represent within subject variability. For the novice surgeons, the variability was an average of the within subject variabilities of five surgeons.

The effects of subtask requirements and constraints are more apparent when cutting suture and dissecting tissue are compared. The two tasks of cutting suture and dissecting tissue were similarly decomposed into two subtasks:

1) pull taut object, and
2) snip object.

The proportion of time spent in each of the two subtasks reveals the effect of object properties on the performance of these two surgical tasks. The lower degree of precision requirement for cutting suture compared to dissecting tissue is apparent from the timeline analysis (Fig. 5). In all subtasks, novice surgeons spent slightly more time manipulating tissue than suture. The expert surgeon, on the other hand, spent less time pulling taut tissue than suture, and significantly more time in snipping tissue than in snipping suture.

The proportionately greater time duration spent by the expert surgeon in snipping tissue over snipping suture may be due to the greater precision and safety constraints required in handling tissue compared to suture. The effect of precision and safety constraints on performance was not as pronounced for the novice surgeons.

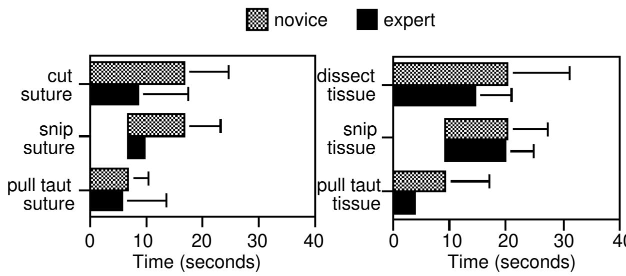

Figure 5. Timelines for cutting suture and dissecting tissue. Left: Timeline compares the average times spent in each subtask of cutting suture for an expert surgeon (n=3) and four novice surgeons (n=8). Right: Timeline compares the average times spent in each subtask of dissecting tissue for an expert surgeon (n=5) and five novice surgeons (n=35). Note that the subtask of pull taut tissue for the expert surgeon shows no variability, as it represents data from only one single trial. All other variabilities represented by the error bars are average within subject variabilities.

3.2 Motion Analysis

Detailed motion analysis revealed that all of the tasks and subtasks could be broken down to five distinct, basic motions (see Table 2 for description): reach & orient, grasp & hold/cut, push, pull, and, release.

This important result was not anticipated when the motion analyses were planned.

Reach & orient was seen whenever the surgeon reached with a tool to grasp or cut a piece of tissue. Occasionally, the surgeon was able to coordinate the reach component with the orient component in one smooth motion. More often, the reach occurred separately from the orient, such that the tool was rotated to the correct orientation after the end-effector has reached its target.

In grasp & hold/cut, the end-effectors of the graspers or scissors opened and closed upon the tissue. Because cutting or snagging other tissues and arteries inadvertently was a concern, the scissors were usually closed as they reached for the target. Also, as the jaws had to be rotated in orientation after the reach, it was safer to have the jaws closed until the surgeon was ready to use it. This behavior was observed in all surgeons, and was especially apparent in cutting tasks with the scissors. Whereas the closing of graspers result in a stable hold of the object, closing the scissors result in the separation of the object.

Pushing motions were observed in suturing tasks when the surgeon pushed the needle through the tissue. These motions were also observed in other tasks when the surgeons appeared to be struggling with the tools. Pulling motions were observed with the graspers and needle drivers/holders in all four surgical tasks analyzed, where an object in stable grasp was pulled against a resisting force.

A release motion was noted when the end-effectors of graspers or needle drivers/holders opened to release the object in grasp, either intentionally or not. Slips of suture or tissue from the closed jaws after seemingly stable grasp, resulting in a re-opening of the jaws to re-grasp, were also considered releases. By the same token, scissors' actions which did not cut when the end-effectors closed, resulting in a re-opening of the jaws to re-cut, were also considered to be release motions.

Motion analysis results for each subtask of the four surgical tasks (suturing, tying knots, cutting suture and dissecting tissue) were compared to motions described for each task in an 'ideal' situation, which provides a baseline measure of minimum motions required. The 'ideal' situation is one where all six degrees of freedom are available for tool manipulation, and where all first attempts of the motions are successful. For example, using the same needle drivers/holders, a simplified laparoscopic square knot can be tied quickly and efficiently with a total of five reach & orient motions, two grasp & holds, two pulls, and one release motion, executed as follows:

Subtasks	**Motions**
1: position needle	***1***. reach & orient (needle driver),
	2. grasp & hold (needle with driver),
	3. reach & orient (needle holder),
2: loop	***4***. reach & orient (driver with needle),
	5. reach & orient (driver with needle),
3: pull through loops	***6***. reach & orient (needle holder),
	7. grasp & hold (suture with holder),
	8. pull (suture with holder),
4: pull knot tight	***9***. pull (suture with driver and holder),
	10. release (suture from both).

However, both the expert and the novice surgeons made more movements than the 'ideal' situation (see Fig. 6).

The effects of the constraints in laparoscopic surgery manifest themselves to a greater extent in the performance of novice surgeons. With less experience and skill, the novice surgeons made more repetitions of the required motions (goal-directed movements), and other 'additional' ones that resembled groping and exploration. These movements suggest that the surgeons were trying to sort out the visuomotor mapping between the video image and their hands. Although these motions are additional with respect to the 'ideal' situation, they may be necessary to accommodate the constraints in laparoscopic surgery.

A comparison of the frequencies of motions in each subtask revealed inconsistencies between the expert and the novice surgeons. In some instances, the novice surgeons performed more movements in one motion category, while in other instances, the expert surgeon performed more movements within one motion category. Nevertheless, the duration of each subtask for the expert surgeon remained shorter than for the novices.

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Table 2. Description of the five elemental motions and their movement coordinate axes.

Motion	Description	Movement Coordinates
Reach & Orient (**m1**)	• movement of tool in any direction toward or away from target • rotational movement of tool about tool insert point	• translation along z-axis • rotation about z-axis • x and y axes
Grasp & Hold/Cut (**m2**)	• open and close movement of jaws	• open/close about the jaw coordinate system
Push (**m3**)	• movement of tool into target tissue, usually with end-effector closed	• translation along z-axis • rotation about z-axis • x and y axes
Pull (**m4**)	• movement of tool away from target tissue, usually with object in stable grasp	• translation along z-axis • rotation about z-axis • x and y axes
Release (**m5**)	• open jaws	• open/close about the jaw coordinate system

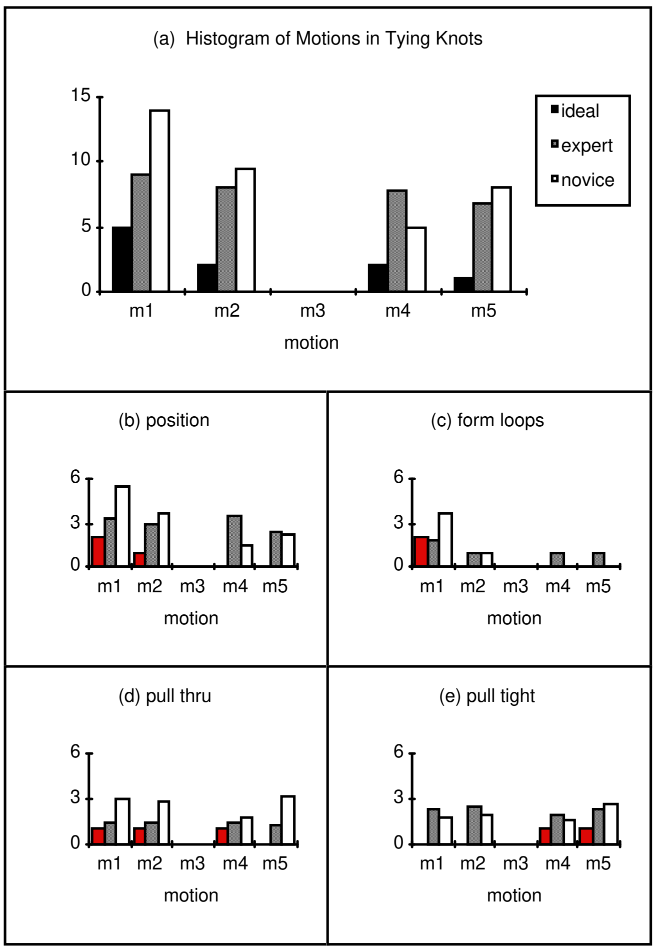

Figure 6. Motions involved in tying a simplified square knot. The frequencies of the five motions in each subtask made by the expert and novice surgeons are compared with the 'ideal' numbers, where m1= reach & orient, m2= grasp & hold/cut, m3= push, m4= pull, and m5= release. Note that there are no pushing motions required in tying a knot in laparoscopic surgery.

4. DISCUSSION

4.1 Novice vs. Expert

As expected, novice surgeons took longer than the expert surgeon to perform the surgical tasks, as well as each of the individual subtasks (Fig. 3, 4, and 5). Differences between novices and the expert were visibly smaller for the dissecting tissue task than for the other tasks. Novices also required more motion attempts in total, to achieve the task goals (shown in Fig. 6 for knot tying). Interestingly, although the expert surgeon had less attempts for reaching & orienting, and grasping & holding, he had more attempts for pulling and releasing in the subtask of positioning needle. The surgeon appeared to have a strategy for positioning the needle, which despite the greater number of motions made, allowed for a faster performance (see Fig. 4 for times spent in subtasks). Given that the above is based on only one expert surgeon, we can not conclude that expert surgeons make fewer movements than novice surgeons. However, it is clear that novice surgeons make movements that are much slower than the expert surgeon. Perhaps experience will optimize the number of motions required to achieve the task goals quickly.

4.2 Task Constraints

Comparing the four tasks, suturing took the longest time, followed by tying knots, dissecting tissue, and cutting suture. These results may reflect four types of constraints: physical, precision, safety, and visuomotor constraints. In laparoscopy, physical constraints stem from the very nature of minimally invasive surgery (or minimal access surgery). Physical constraints are due to the single, small port of entry for each tool, and the crude design of the tool itself. Surgical tools, with a long shaft which extends the reach of the effector from the hand, can reach the operative site through trocars, but have reduced degrees of freedom for subsequent maneuvers.

In general, endoscopic manipulators have been designed to resemble their counterparts in open surgery. The end-effectors of graspers, scissors, and needle drivers/holders have one action: open/close. This action can be identified as an elemental prehension movement: grasping. Forces are applied, in opposition by the jaws of the tool end-effectors to the target object. The scissors end-effectors, with their sharp edges, shear the object with their closing

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motion. The gripping jaws of the graspers and needle drivers/holders, on the other hand, maintain a static gripping posture with constant contact points on the object. Motion can be imparted to the object by translation/rotation movements of the entire tool, or by releasing grasp and relocating the tool's contact points on the object: repositioning or regrasping. Other forms of contacts typical in performatory hand movements such as rolling or sliding (see MacKenzie and Iberall, 1994, p.269) are not possible. For example, the ski needle, used in suturing, can not be rotated into the desired orientation by rolling the needle on its side between the jaws of the needle holders. The surgeon must perform many incremental regrasping movements to achieve the desired orientation of the needle. This process is time-consuming and requires that the surgeon perform a series of additional motions to reach the task goal. The more complex the manipulative movements that are required in a task, the more additional motions are performed. These additional motions are discrete, single or two degree-of-freedom motions that are restricted by the tool's reduced degrees of freedom

This becomes obvious when suturing or tying knots are compared with cutting tasks. Given the same degrees of freedom in tool manipulability, the task which requires the greater number of subtasks and motions is the more complex. Therefore, suturing and tying knots are more difficult than cutting tasks, while dissecting is more difficult than cutting suture. However, other constraints also contribute to the overall perception of task difficulty. Safety and precision constraints are often defined by task requirements and properties of the target objects/tissues.

4.3 Properties of Target Object

Safety constraints in laparoscopic surgery vary with task requirements. For example, the task of dissecting tissue imposes a greater safety constraint than the task of cutting suture, even though they have two similar subtasks: 1) pull object taut, and 2) snip object. The object (tissue or suture) to be divided in each task determines the degree of difficulty.

We saw in Fig. 5 that the difference in task duration between expert and novice surgeons was more pronounced for cutting suture than for dissecting tissue. There was a dissociation at the subtask level in that for dissecting tissue, novice-expert differences in duration were more pronounced for pulling taut the tissue, i.e., the alignment prior to snipping the tissue; in contrast, for cutting suture, novice-expert differences in subtask duration were more evident for the subtask snip suture, i.e., to align the snip for the very small suture.

Looking at the number of motions in each subtask of snipping (see Fig. 7), the greater number of motions in snipping tissue over snipping suture may reflect a greater safety constraint perceived by the surgeons. In snipping tissue, the location and size of the cut needs to be controlled. As well, the risk of snipping the wrong tissue or surrounding tissues and arteries is a major safety concern. Because of these safety constraints, snipping tissue is more difficult than snipping suture.

In contrast, the greater number of motions in the subtasks of 'pulling taut the suture' compared to 'pulling taut the tissue' indicates that it is more difficult to grasp suture. This can be explained by examining the precision requirements in the subtasks.

In the subtasks of grasping tissue or suture to pull taut, for the purpose of dividing, the same basic safety constraints underline both subtasks. In addition, the object to be grasped is both a physical constraint and a precision constraint. The suture is smaller and requires greater precision to grasp with the tool. Tissue, on the other hand, is larger in surface area, such that the same degree of precision to grasp is not required. As well, the orientation of the jaws need not be in-line with the direction of the object, as for a piece of suture. There appears to be more 'release' motions in grasping for suture (Fig. 7), which suggests that the suture is difficult to hold in stable grasp.

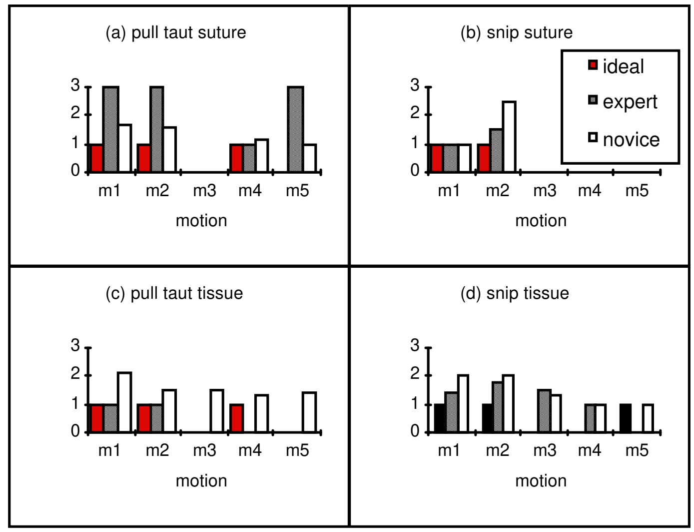

Figure 7. Contrasting the motions involved in the tasks cutting suture and dissecting tissue. m1= reach & orient, m2= grasp & hold/cut, m3= push, m4= pull, and m5= release.

Precision constraints, compounded with safety and physical constraints, add to the perceived difficulty of surgical tasks. In suturing, the precision required to place stitches in the tissue, to take an appropriate bite size of the tissue by the needle, and to line up the second stitch with the first stitch, become more significant as it can also be perceived as an additional safety constraint. For tying knots, precision is required to handle and manipulate suture which is thin and slippery. Again, the physical constraints presented by the size of the suture increase the precision constraints for tying knots and add to the perceived difficulty.

4.4 Motions, Relative to Unconstrained Ideal

The finding that all the subtasks reduced to the same basic, underlying motions was unexpected. The surgeons' movements with the endoscopic tools were reduced to five elemental manipulation motions:

1. reach & orient,
2. grasp & hold/cut,
3. push,
4. pull, and
5. release.

For all tasks, we compared the number of motions that expert and novice surgeons made to an Ideal, unconstrained performance (shown in Fig. 6 for knot tying). In all cases, both novice and expert surgeons made more motions than the unconstrained ideal. We have discussed above how this is due, in part to the physical constraints of

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the tool and task. Repeated observations of the motions on the video revealed however, that these were not always repeated attempts at the same motion; rather, it was clear that some of these movements were goal-directed and intended to get relational information about depth, orientation, distances, etc. They were not exploratory movements to obtain specific structural properties of the objects per se (Lederman & Klatzky, 1987). The movements were information gathering in order to execute subsequent task motions. This is much like the distinction between epistemic and pragmatic actions (Dr. L Turner, personal communication, June 7, 1995).

4.5 Difficulties in Orienting and Positioning Tools

The task analysis showed the greatest difficulty (for both novice and expert surgeons) for those subtasks which required positioning or orienting of the tool end-effector. Also, the differences between novices and expert were particularly evident in these subtasks.

Similarly, the motion analysis showed that more motions were required to accomplish tasks which require the orientation of the tool end-effector, or the object (needle and suture). Overall, novice surgeons seemed to require more motions in total to achieve the task goals than the expert surgeon. Hence, they require more time to complete the tasks. However, results suggest that novice surgeons also make slower movements than the expert surgeon (see discussion in 4.1). This may be due to the effect of inexperience, combined with the effects of various constraints in performing surgical tasks laparoscopically.

4.6 Serial Organization of Reach and Grasp

The five elemental motions, in various combinations, are observable in natural human prehension and direct manipulation of objects (MacKenzie & Iberall, 1994). Reaching and grasping (preshaping and enclosing, prior to contact) are typically performed in parallel when humans perform goal-directed prehension movements (Jeannerod, 1984), and are characterized by a transport component of the wrist, and a grasp component of the hand. The hand typically opens during the transport of the hand in space towards the object to be grasped, and closes around the object at the end-point of the transport trajectory. These same movement components are observed in laparoscopic surgery, but in series. The jaws are closed while the tool is being transported. At the endpoint of the transport trajectory, the jaws open to grasp (see Fig. 8). However, motion analysis of tasks and tools revealed performance characteristics that can be likened to simple robotic single-jointed movements. Simple robotic movements are sometimes seen to be a sequential series of uni-directional motions that lack the appearance of smooth coordination between multi-joints.

It may be that surgeons are forced to slow down and perform the motions in sequential order due to various constraints. The slow motion in task performance may be a result of uncertainty in position and orientation within the abdominal cavity. Motions that are performed one at a time may be one way to minimize the many constraint variables for maneuvering in the operative field by reducing the degrees of freedom. Therefore, it suggests that constraints in laparoscopic surgery impose additional information processing demands on the surgeons, such that motions that are normally executed in parallel in natural prehension must now be planned and executed in serial order.

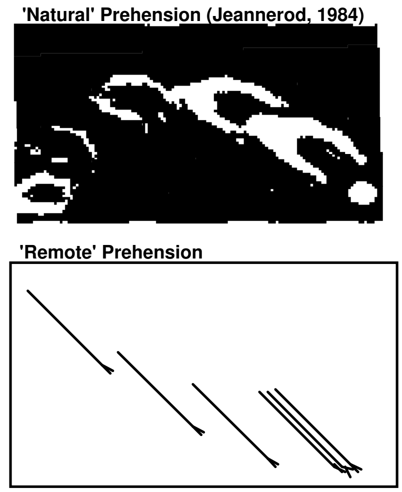

Figure 8. Comparison of reaching and grasping in natural prehension and prehension with a tool in laparoscopic remote manipulation. The parallel ordering of the transport and hand formation components were described by Jeannerod (1984). The same components of reaching and grasping are also seen in laparoscopic remote manipulation. However, the two components are performed in serial order.

4.7 Other Issues

Although issues related to imaging were not examined in this study, they are important for understanding the overall effect of increased information processing demands on the surgeons' performance. From our task and motion analyses, the longer time taken to perform surgical tasks laparoscopically can be indicative of the increased difficulty in matching the visual feedback with the motor map during hand movements. The impact of various aspects of 3-D technology on the surgeons' performance is still unknown, and need to be further investigated. Preliminary studies have been conducted to evaluate the cost and benefit of 2-D and 3-D viewing systems for endoscopic surgery (e.g., Pietrabissa, Scarcello, Carobbi, and Mosca, 1994, Crosthwaite, Chung, Dunkley, Shimi, and Cuschieri, 1995).

Another issue raised by our findings in the motion analysis is concerned with the unique characteristics of the surgeons' movements. We found that surgeons make movements that are slow, sequential, and uni-dimensional. In addition, surgeons performed additional movements in the unfamiliar, 2-D operative environment. There is a need for more detailed, three-dimensional motion studies to understand the nature and purpose of these movements. Also, instrumented laparoscopic holding mechanisms and devices which are equipped with force/moment sensors (Faraz, Payandeh, and Nagy, 1995) can be used to gather quantitative measures of motions and forces generated during performance.

Implicit in our analysis of the tasks and the motions involved in performing laparoscopic surgery is the issue of task forces that are required to effect the target states in each task, with appropriate forces applied by the hands and tools on the objects to be manipulated (e.g., to hold the needle or suture). With the reduced dexterous manual control of the tools, and reduced tactile and force feedback for the surgeon, it is expected that surgeons take longer to process the limited force feedback, increasing the muscular and mental effort in surgery. This issue has implications for the management of cumulative trauma disorder (e.g., carpal tunnel syndrome) in surgeons (Cao, 1996). Force-reflecting tools may be developed for use in combination with 3-D vision systems (e.g., Hill, Jensen, Green, and Shah, 1995).

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