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Evaluating Control Modes for Constrained Robotic Surgery

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Abstract

Minimally invasive surgery (MIS) constrains instrument motions to 4 DOF by precluding lateral motion at the incision. Robotic MIS systems can interpose arbitrary mappings between the surgeon's motions at the master controller and the motions of instrument tips within the patient's body. Our goal was to find the interface that was easiest to learn. We investigated the effects of different coordinate frame mappings (screen-mapped versus instrument-mapped) and master dexterities (6 DOF versus 4 DOF) by means of performance measures on simple surgical tasks. All four mode-dexterity combinations had approximately the same time-to-completion. The combination of instrument-based mapping and 4 DOF master had lower error rate and lower subjective workload. This mode most clearly reproduces the task constraints within the patient's body.

1 Introduction

Traditional surgical methods require a large incision in the patient's body in order to reach the desired area and to afford adequate space for the surgeon's hands to work. In contrast, minimally invasive surgical (MIS) techniques involve the insertion of long, thin surgical instruments through small incisions, and the entire surgical procedure is carried out by the manipulation of the tool handles from outside the patient's body. These procedures result in reduced patient pain and trauma, fewer complications, and shortened convalescent periods.

However, surgeons face many challenges in making the shift from open surgical techniques to MIS techniques. These include decreased visual and haptic information, significant motion constraints, and the need for cognitive remapping between visual and motor frames.

Since the instrument passes through a port and is effectively constrained by a pivot point, motion is constrained to 4 degrees of freedom (DOF) (Melzer et al., 1992). Excluding the end-effectors, the 4 DOF are: (1) translation along the shaft of the tool, (2) rotation around the translational axis, (3) & (4) limited inclination of the shaft pivoted through the incision.

Cognitive remapping is necessary in order to resolve the incompatibility of the viewpoint presented by the endoscope and the spatio-motor expectations of the surgeon. Cognitive remapping is also needed because in MIS the surgeon is controlling the instrument tip via back-of-the-handle techniques. The pivot constraint of the entry port necessitates a movement of the instrument handle outside the body in the reverse direction to the desired direction of the instrument tip. Previous inquiries into the effects of reversed hand-tool motion control (Hodgson et al., 1997) have, as expected, emphasized the advantages of avoiding such reversed control methods. Similarly, studies comparing knot-tying and suture task performances for hand versus endoscopic instruments showed that task times with endoscopic instruments were about twice as long (Tendick et al., 1993).

The purpose of this study is to implement and evaluate a minimally invasive surgical interface whereby the surgeon can maintain as natural a spatio-motor mapping as possible and avoid reversed handle-tip instrument control methods. A way to achieve this while retaining the benefits of MIS is to interpose a robotic system between the surgeon and the patient which will act as a translator between the open surgery-like motions of the surgeon and the corresponding endoscopic motions required at the patient. Thus the surgeon's hands would essentially be working at the tool tips inside the body as opposed to working from outside, controlling the back of the handle of the instrument. This involves the design of a human-machine interface that enables 6 DOF at the master end and a minimally invasive surgical robotic system at the slave end.

In some cases, the addition of a wrist at the end of the instrument inside the body would resolve many of the motion constraint issues by adding another 2 DOF. However, such a design adds considerable cost, particularly in microsurgery applications such as opthalmic surgery where miniaturization of the wrist joint is extremely difficult. Our goal is thus to find the interface easiest to master for a 4 DOF constrained slave robot. A similar concept with a 4DOF master interface and one mapping has been implemented (Hill and Jensen, 1998) and in-vitro experiments have indicated the advantages of such a system as compared to conventional endoscopic instruments.

2. Methods

2.1 Experimental System

The experimental system included two Phantom Haptic Interfaces (Model 1.5, Sensable Technologies, Cambridge, MA) interfaced to the slave robots from a ZEUS robotic surgical system (Computer Motion, Inc., Goleta, CA). The commercially-available Zeus system comprises three positioner robots and a surgeon console (Fig. 1). Two robots position the left and right instruments, and a third positions the endoscope that feeds back an image of the operative site to a monitor.

The surgeon console consists of a monitor and a seated station whereby the surgeon can control the positioner robots via handles resembling traditional laparoscopic instruments. During surgery, the motions of the instrument-holding robots are controlled by the surgeon while seated at a console located a short distance from the operating table. The console supports two master mechanisms, one for each hand, and houses the robot controllers and the video display. The left and right master mechanisms each have five degrees of freedom (including grasping) that mimic the motions of a laparoscopic instrument. Four of these axes are passive, however the grasping degree of freedom includes force feedback of the grasping forces measured at the instrument end. The motion of the camera holding robot (AESOP) is controlled using voice commands. For these experiments, the Zeus master mechanisms were replaced by the Phantoms as master controllers.

Each Zeus positioner is a geared, servomotor-driven mechanism that attaches to the rail of the surgical table. The robots have six degrees of freedom with two passive joints at the instrument/laparascope end (joints 4 & 5 in Fig. 1). The instrument positioner is similar to the laparascope positioner but with the addition of gripper open/close. For initial set up, the positioners can be moved manually by pressing a Manual Mode Button on the robot arm. This feature is also used to set a motion limit on joint 1, which limits lower robot arm travel to ensure patient safety.

Encoders on each Phantom established a location in 3D space of the tip of the stylus (the input device) as well as the roll at the stylus. A switch was incorporated into the stylus to enable open/close of the instrument gripper. The use of two Phantoms enabled the simultaneous control of a left and right instrument. Note that force feedback was not provided. The surgeon console consisted of a seat with adjustable armrests and Phantoms situated in front at either side, with a high-resolution video monitor placed at a comfortable eye-level position in front of the subject (Fig. 2). A foot pedal acted as a toggle switch to activate the system. Upon deactivation of the foot pedal switch, the instrument tips at the slave remained fixed until reactivation, regardless of movement of the stylus in the interim. This allowed repositioning of the master to maintain a comfortable workspace for the surgeon.

The scale of movement between master and slave could be adjusted, allowing the manipulation of instruments on a microsurgical scale while utilizing normal hand and arm movements. The scaling ratio in these studies was set to approximately 4 to 1, with each movement by the surgeon resulting in a movement a fourth the size at the robotic surgical instruments.

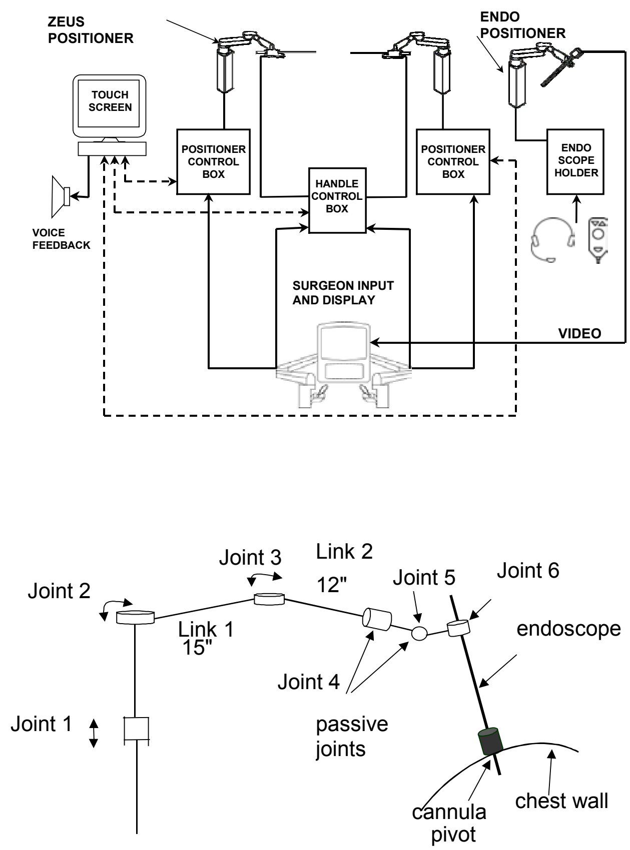


Figure 1. Above: block diagram showing Zeus system components. Below: Zeus positioner robot link diagram. Endoscopic robot shown; instrument robots are similar.

Figure 2. Phantoms as master controllers with 6DOF interface. The 4DOF interface is implemented by extending the stylus backwards through a constraint.

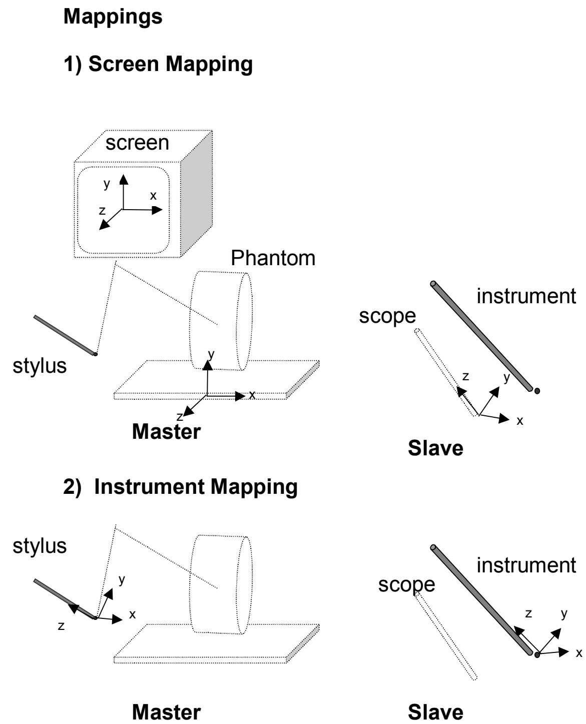


Figure 3. Two mapping modes

2.2 Mapping

The mappings tested (Fig. 3) were:

1) Body-based Cartesian frame at master to image-based frame at slave. This mapping enabled motion in the world frame to correspond with what was observed in the video image. For example, in this frame an upward motion of the stylus tip resulted in an observed motion of the instrument tip in the video image towards the top of the screen.

2) Stylus-based frame at master to instrument-based frame at slave. The frame was attached to the stylus tip in this case and mapped to the instrument tip. This frame followed the stylus tip and was continually updated. Thus, for example, a movement along the axis of the stylus would result in a corresponding movement of the instrument along its axis.

2.3 Dexterity

Two different levels of dexterity were tested, each level examined with each mapping (Fig. 4). These were:

1) 6 DOF: The stylus tip could be moved to any position and orientation in space without restriction.

2) 4 DOF: The stylus tip was confined to 4 degrees of freedom with the loss of two rotational degrees of freedom (pitch and yaw) by the use of a constraint that provided the same constraint as the slave. The constraint was introduced by extending the stylus with a rod and passing the other end of the rod through a tripod-mounted constraint point located above and behind the operator's shoulder. The rod length was chosen to reflect the angular relationship between the incision and the slave instrument.

2.4 Tasks

The tasks to be completed in the various modes were:

1)Square-knot tying
2)Suturing

These were chosen as representative of the tasks required in endoscopic surgery. The tissue to be sutured was simulated by means of a latex glove. The procedure involved tying a knot (square knot) and then running four suture stitches on a dot pattern imprinted on a surgical glove. The dot pattern was present to serve as a suturing template and had 0.052 cm diameter dots and 0.102 cm matrix spacing. The suture was 7-0 Prolene with 3/8 curve, 9 mm needle and suture cut to 5 cm.

The glove was stretched over a frame and placed in an endoscopic trainer, which is a raised platform placed at the slave end to simulate the patient. Cannulae were placed in ports in this platform to simulate incision points. Two instruments with grip capabilities and an endoscope were placed in these ports, as illustrated in Fig. 5.

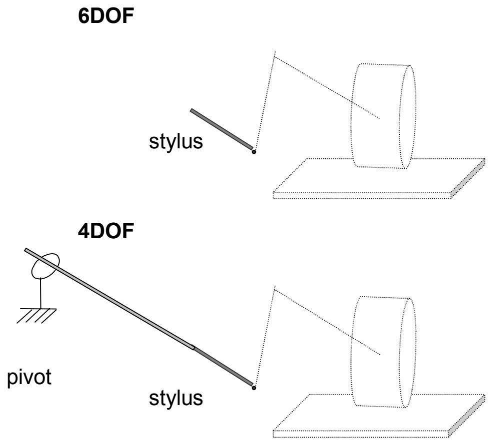


Figure 4. Two master dexterity configurations

2.5 Performance measures

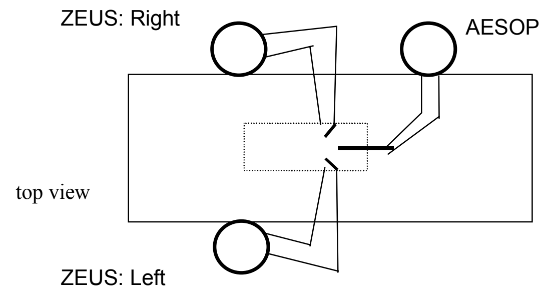
We selected six performance measures:

1) Knot-tying time.
2) Suture-running time.
3) Accuracy: Percentage of dot through which the suture passed (out of ten).
4) Error count: Errors and difficulties were noted. Types of errors that were counted were bending of the needle, breakage of the suture, and tearing of the glove/tissue.
5) Ease of interaction: Subjective ratings of interface interaction were noted on a scale of 0=very difficult to 10=very easy.
6) Fatigue level: Subjective ratings of fatigue experienced were noted on a scale of 0=no fatigue to 10=severe fatigue.

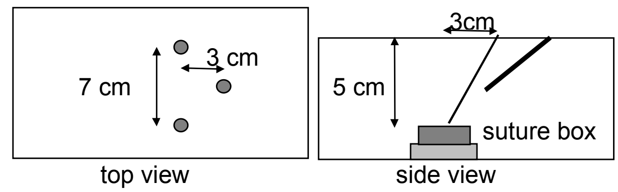
2.6 Subjects

Four subjects (male and right-handed) were recruited who had no prior surgical training or experience with any of these interface modes. These subjects were trained to perform these standard surgical tasks. Surgical instruments used in open surgery, such as forceps and needleholder, were used to train the subjects to become proficient in the mechanics of these tasks. The training tasks were carried out in an open surgery manner and the subjects were able to view their hands, the instruments, and the surgical task directly. They were also instructed on the techniques of productive and efficient surgical task execution (Anderson and Romfh, 1980). This enabled learning of the task to take place before the actual experimental trials with the various modes so that as far as possible differences between modes could be attributed to learning of the interface and mode of control.

Positioner robot setup



Trainer box setup



7 cm between the instrument ports.

5 cm from the top of the trainer to the suturing glove (and box) surface.

3 cm (horizontal distance) between the instrument ports and the suturing target.

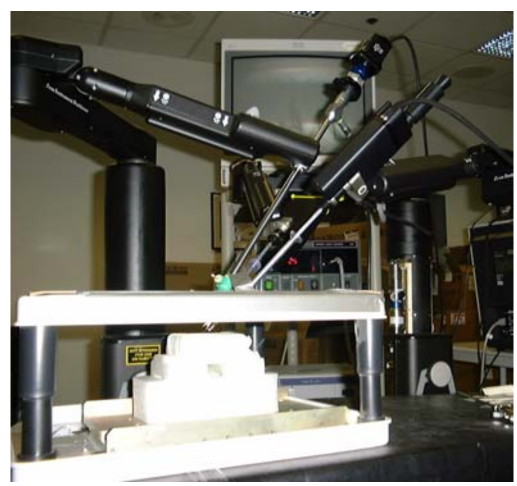


Figure 5. Zeus slave configuration: two instrument positioners and one endoscopic positioner inserted into an endoscopic trainer box.

2.7 Experimental Design

The modes of control to be examined were:

1) Screen-mapped with 6 DOF (Scr6)
2) Screen-mapped with 4 DOF (Sc4)
3) Instrument-mapped with 6 DOF (Instr6)
4) Instrument-mapped with 4 DOF (Instr4)

Each subject underwent 8 trials with each mode. A trial consisted of a knot-tying and suture task. The subjects were instructed to complete the task as quickly and efficiently as possible while maintaining the accuracy of placement of suture through the dots and quality of the constructed knot and running suture. In order to minimize the effects of learning, each subject was presented with the modes in different orders, arranged in a 4x4 Latin squares design.

At the first trial subjects were instructed on the basics of the interface. Before the first trial in each mode the subjects were exposed to an orientation session for that particular mode and allowed 15 minutes to attain some level of familiarity and utility with the interface by means of simple pick-and-place positioning and peg-in-hole insertion tasks.

3 Results

3.1 Comparison of mode averages

The comparison of the measures among the 4 modes is displayed in Figure 6. The symbols superimposed on the columns denote individual subject averages. Fig. 6(a) shows that the different modes present the same level of performance in terms of knot-tying time. This was confirmed by means of ANOVA's (Analysis of Variance) which failed to reach significance at the 95% confidence level. The average knot-tying time was about 120 seconds and the lowest knot-tying time was 40 seconds. For suturing, the significance level also did not confirm any difference between the modes in terms of this performance measure. The average suture task completion time was 180 seconds and the lowest was 55 seconds.

Fig. 6(b) shows that accuracies both in and out of the glove do not vary significantly between modes. Error counts are compared in Fig. 6c. There is a significantly lower number of errors with Instr4 as compared to the other modes. This was confirmed by means of ANOVA's and *t*-tests with each of the other modes.

Comparison of the modes via the subjective ratings of interaction ease shows that subjects in general favored the Instr4 mode by far (Fig. 6d). Subjective ratings of fatigue also reflected the preference for Instr4 in that subjects reported the least fatigue with this mode of control (Fig. 6e).

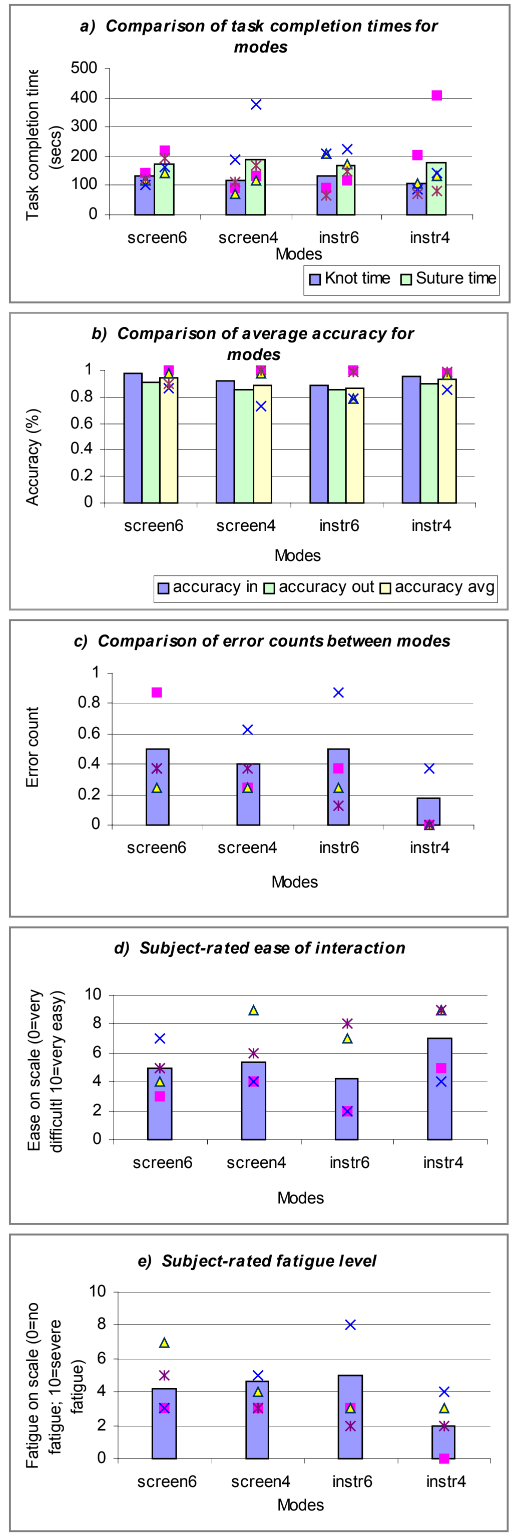


Figure 6. Comparison of the 4 modes by performance measures: (a) knot-tying and suture time, (b) accuracy, (c) error count, (d) interface rating, (e) fatigue rating. Symbols show subject averages.

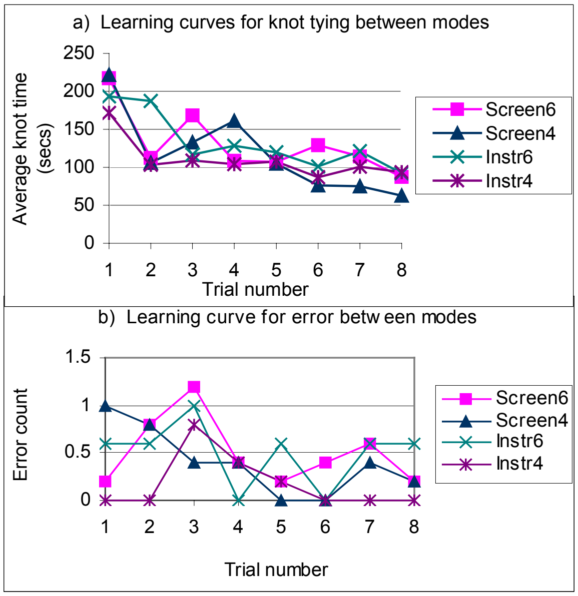


Figure 7. Learning curves averaged over all subjects: (a) knot-tying time, (b) error

3.2 Learning

Learning in terms of knot and suture time from trial to trial in each mode averaged across subjects (Fig. 7a) shows that Instr4 seems the easiest to master, with the best initial performance as well as leveling off the fastest. In general, performance times decreased 50% over the course of the trials.

The error count learning curve (Fig. 7b) shows that Instr4 resulted in the least fluctuation and its curve levels off to zero the earliest. Note in particular that the last three trials of Instr4 were error-free.

There was a discernible learning trend across all the trials, that is, there was some transfer of skills between modes such that in general subjects performed better with the later trials regardless of the mode these trials were presented in. The Latin squares design that presented modes in different orders to each subject sought to minimize the effects of this phenomena on the data for the comparison of the modes. Looking at the performances of the 32 consecutive trials averaged over subject, a 'mode transfer characteristic' could be seen whereby there was a drop in performance level with each mode's initial introduction.

3.3 Statistical ANOVA's

In general, the differences in performance between modes did not reach significance at the 95% confidence level when subjected to 2-way ANOVA's checking for the factors of mapping (screen vs instrument) and DOF (6 vs 4). One-way ANOVA's gave similar results in comparing the 4 modes. However, comparing Instr4 with each of the other modes in turn there was found to be a significant reduction in error using this mode ($p=0.02$).

3.4 Subject Variations

The results for each subject shows that for most performance measures, the mode which yields the best performance varies from subject to subject. This may be due to the different order of presentation in the Latin squares design. The exception is the measure of error, where all subjects committed the fewest errors with the Instr4 mode. The symbols on the columns in Fig. 6 depict subject averages, showing significant variation between subjects. Although all subjects were novices, there were certain subjects who took to the task more quickly than others. One particular subject who was remarkably adept with all modes very much favored the Instr4 mode.

4 Discussion

4.1 Mode comparison

Instrument mapping with 4DOF was notably advantageous, especially in terms of errors committed, speedy habituation to the interface, and subjective preference and fatigue. The Instr4 mode is the one which is the one closest replication of the slave. Addition of a pivot point at the master simulates the constraint of the entry point at the slave. This constraint in effect reduces the confusion that can arise from having 2 extra degrees of freedom at the master as compared to the slave. Subjects also commented that having the constraint there seemed to minimize their fatigue as they engaged in smaller motions than with 6 degrees of freedom. The constraint worked especially well with the instrument mapping because had there been no constraint the subject would have had to make a conscious effort to remember that to move the instrument inward he would have to move the stylus along the direction in which it was pointing.

The instrument mapping also seems to afford a more intuitive mode of control in that the stylus can be regarded as a physical three-dimensional representation of the instrument under control. In the same respect, screen mapping can be thought of as more 1-dimensional. This is because the subject is essentially controlling the one-dimensional tip of the stylus without much room for understanding the physical configuration of the instrument required for that desired tip position.

4.2 Learning

A major result of our study was the absence of a significant performance time difference between modes. One of our goals was to examine the learning of the interface. Considering that these subjects were novices at endoscopic technique as well, the speed with which they became familiar with the interface is quite remarkable. However, it is not possible from our study to draw conclusions about long-term differences between modes. We must note that the effects of the learning of the task mechanics may have overshadowed between-mode effects. A clearer difference between the modes would possibly be seen had the experiments been conducted with surgeons experienced with endoscopic skills.

An appreciation of the differences between novices and experienced surgeons can be obtained by comparing data on the efficacy of the Zeus system versus handheld laparoscopic instruments (Cunningham, 1998). These trials were carried out in the same manner as the above experiment with the exception of the knot-tying task, which consisted of a double loop followed by two single loops. Also, these trials were carried out by experienced surgeons, instead of novices. It can be seen that Instr4 and Zeus give faster knot-tying times than handheld instruments (Fig. 8a). It can also be seen that the Zeus time is smaller than the Instr4 time even with the additional double loop in the task. This suggests the effect of experience and the fact that in our experiment we could only observe the initial training. Fig. 8b further emphasizes the advantages of the robotic surgery interfaces as the suture times for Instr4 and Zeus are lower than for handheld instruments. Finally, it can be seen that the robotic interfaces also increased accuracy level (Fig. 8c).

We should also note the delineation between performance measures for tangible results such as time, versus measures which account for the workload incurred in achieving that level of tangible performance. Thus subjects may have achieved some level of utility with all modes but may have experienced far less workload and stress with some.

A further note should be made regarding inter-subject differences. We have seen that the system is easily usable for some, but very difficult for others. This has also been observed with those with surgical experience who have tried the interface. Those with an extensive endoscopic background struggled with the interface. The difficulty seemed to lie in the fact that the interface used a mapping counter to that used in endoscopy, which these surgeons had invested much effort in learning. One endoscopic surgeon surmised that learning this new interface would involve “unlearning” his present skills. However, cardiac surgeons accustomed to only open surgery were quite taken with the interface, remarking that the hand/wrist motions allowed in using this interface were strikingly similar to those used in open surgery and natural prehension. They attributed their comfort with this interface to the ability to use more wrist/hand motions as opposed to the arm/shoulder motions used in the more conventional endoscopic surgical interfaces.

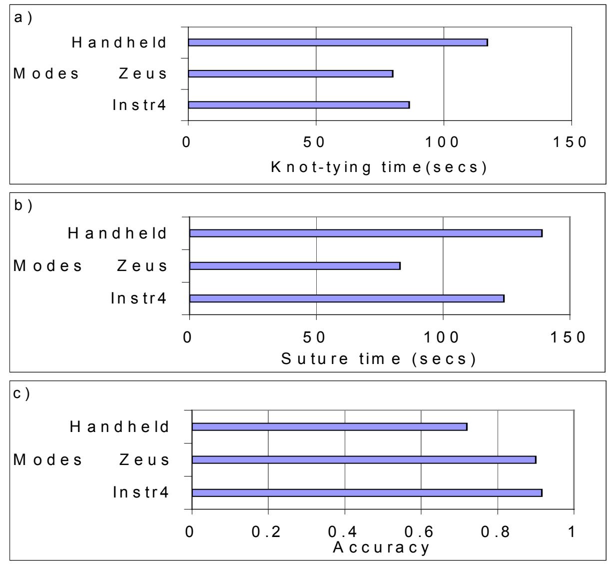


Figure 8. Comparison with trained surgeons using handheld instruments and complete Zeus system: (a) knot-tying time, (b) suture time, (c) accuracy

Acknowledgements

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