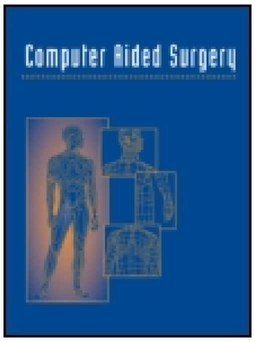

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Computer Aided Surgery, January 2006; 11(1): 21–30

BIOMEDICAL PAPER

Evaluation of an intuitive writing interface in robot-aided laser laparoscopic surgery

HSIAO-WEI TANG[1], HENDRIK VAN BRUSSEL[1], JOS VANDER SLOTEN[2], DOMINIEK REYNAERTS[1], GUNTER DE WIN[3], BEN VAN CLEYNENBREUGEL[4], & PHILIPPE R. KONINCKX[5]

[1]*Division of Production Engineering, Machine design and Automation and* [2]*Division of Biomechanics and Engineering Design, Department of Mechanical Engineering, Katholieke Universiteit Leuven,* [3]*Centre for Surgical Technologies, Katholieke Universiteit Leuven, and* [4]*Department of Urology and* [5]*Department of Obstetrics and Gynecology, University Hospital Gasthuisberg, Katholieke Universiteit Leuven, Leuven, Belgium.*

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Abstract

Objective: The feasibility of the conceptual Intuitive Writing Interface (IWI) in robot-aided laser laparoscopic surgery has been demonstrated previously. This paper investigates the potential improvement of IWI by comparing conventional manipulation (CM) and IWI manipulation (IM) and conducting an animal experiment.

Materials and Methods: Three tasks were designed that were considered to be representative of laser laparoscopic surgical procedures. All test participants used both CM and IM in all tasks. Completion time and error level of each task were taken as comparative indices and were integrated into a self-defined Index of Time and Error (ITE). Six sequential *in vitro* trials were carried out to investigate learning curves. In addition, nephrectomy was performed on a rabbit by employing IWI in robot-aided laser laparoscopic surgery.

Results: The results showed significant advantages for IM, with shorter completion time, more successful shots, and smaller error length in the three tasks, as compared to CM. The learning curve showed a promising trend for IM. More than half of the participants performed better with IM. The animal model experiment demonstrated the clinical feasibility of IM, but at the same time revealed some limitations.

Conclusions: The new IWI interface definitely improved laser laparoscopic procedures by taking advantage of familiar writing skills. With its flexibility of implementation and ease of use, IWI has clear potential for use in laser laparoscopic procedures.

Introduction

Lasers have been widely applied in medicine. Their potential advantages, such as lack of physical contact, reduced blood loss, precision, and limited fibrosis and stenosis, have encouraged their clinical use [1]. In gynecological endometriosis treatment, for example, operative laparoscopes with CO_2 lasers have become a powerful tool for both inspection and ablation of lesions [2]. However, the reduced dexterity and hand-eye coordination with Minimal Invasive Surgery (MIS) instruments may jeopardize the efficiency and safety of the procedures [3].

Good surgical technical skills are becoming increasingly important. According to Spencer [4], 75% of the success of a good surgical intervention is due to the decision-making process and 25% to dexterity. In MIS procedures, dexterity might play a more important role [5] because of the aforementioned problems. Until now, standards or objective criteria for assessing the quality and performance of

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Correspondence: Hsiao-Wei Tang, Division of Production Engineering, Machine Design and Automation, Department of Mechanical Engineering, Katholieke Universiteit Leuven, Celestijnenlaan 300B, 3001, Heverlee, Belgium. Tel: +32 16 322768. Fax: +32 16 322987. E-mail: Hsiao-Wei.Tang@mech.kuleuven.ac.be

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a surgical intervention have been mostly based on the opinions of senior colleagues. In response to technological advances and the increasing demand for assessment of surgical skills, several approaches have been employed, ranging from direct observation through psychomotor testing and motion analysis to virtual reality (VR) [6]. For MIS procedures in particular, extensive training is required to acquire the skills necessary to manipulate the instruments and perform techniques such as suturing. Dedicated programs have been designed to help medical students and novice residents acquire these skills [7], and objective surgical skill assessment would be beneficial for providing validated, reliable and standardized information. It could be applied to improve training program design and surgical skill certification, and would permit inter-institutional comparison, as well as increasing public confidence.

Recently, the conceptual Intuitive Writing Interface (IWI) was successfully implemented and tested in laser laparoscopic surgery [8–10]. Since laser ablation is a non-contact technique that is visually analogous to a drawing action, the aim of the IWI was to resolve the problems of disparity and dexterity. The robot holds and steers the laparoscope, whilst the surgeons employ 2-degrees-of-freedom (2-DOF) writing skills on a digitizer tablet to control laser ablation (Figure 1). The control scheme was dubbed *What You Draw Is What You Cut* (WYDIWYC). This took advantage of human handwriting skills and replaced conventional 7-DOF whole-arm manual laparoscope manipulation. The zoom in/out action was obtained by pushing buttons on the digitizer pen. As a result, the IWI was shown to be effective in both laparoscope inspection and laser ablation. Experiments involving writing characters on an apple using the IWI in a simulated surgical environment demonstrated that the laser ablation quality could be improved to the level of handwriting and even beyond (Figure 2). The IWI and WYDIWYC concepts can be applied to most commercial laparoscope-holding robots, as the available degrees of freedom of the MIS instruments are identical.

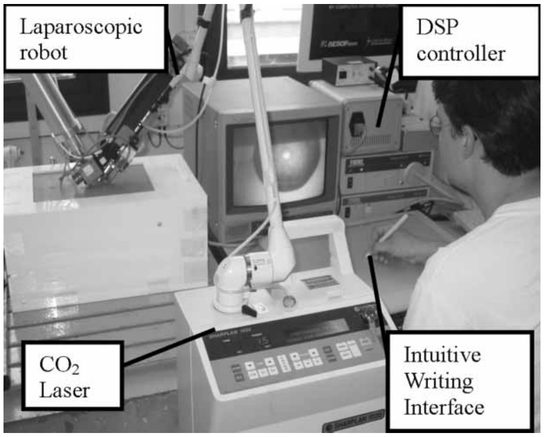


Figure 1. Complete system setup in a simulated surgical scene. The user looks at the screen to use the IWI. The robot and laparoscope were installed around a phantom box. The camera transmitted the images (of an apple) inside the phantom to the TV screen.

This paper reports a new experiment designed to assess the system's performance in the hands of volunteers with a medical background and to compare the differences between conventional manipulation (CM) and IWI manipulation (IM). The skill assessment took into account features of laser ablation procedures as well as laparoscopic navigation. Finally, to obtain more information about the performance of the IWI technology in real-life surgery, an animal experiment was performed by experienced surgeons.

Materials and methods

Equipment

An operative laparoscope (Hopkins 26075AA, Karl Storz GmbH & Co., Tuttlingen, Germany) with a laser channel was employed, together with standard laparoscope accessories such as camera systems and illumination devices. The CO$_2$ laser was a Sharplan 1030 coupled to a reflective mirror system inside an articulating arm. The laser trigger was a foot pedal. The developed IWI system consisted of a robot manipulating the laparoscope, a pen and tablet writing interface, a digital signal processing (DSP) controller and a PC. The applied robot was a FIPS endoarm [11], a prototype developed for solo surgery (provided by Karl Storz Gmbh & Co.). It was originally designed as a laparoscope-holding robot and had been intentionally modified for the research. The phantom box was a standard MIS training box.

Manipulation setup

Two manipulation setups were created to simulate an operating room (OR) environment in the Centre for Surgical Technologies (CST) of the Katholieke Universiteit Leuven.

1. The conventional manipulation (CM) setup simulated the real-world situation in the OR. The participants were asked to stand near the phantom box with one hand manipulating the laparoscope using visual feedback from the TV screen in front of them. Referencing the red spot displayed on the screen that indicated the cutting position of the laser, participants triggered the laser by operating the foot switch to perform the ablation.
2. The IWI manipulation (IM) setup employs the robot to manipulate the laparoscope and laser.

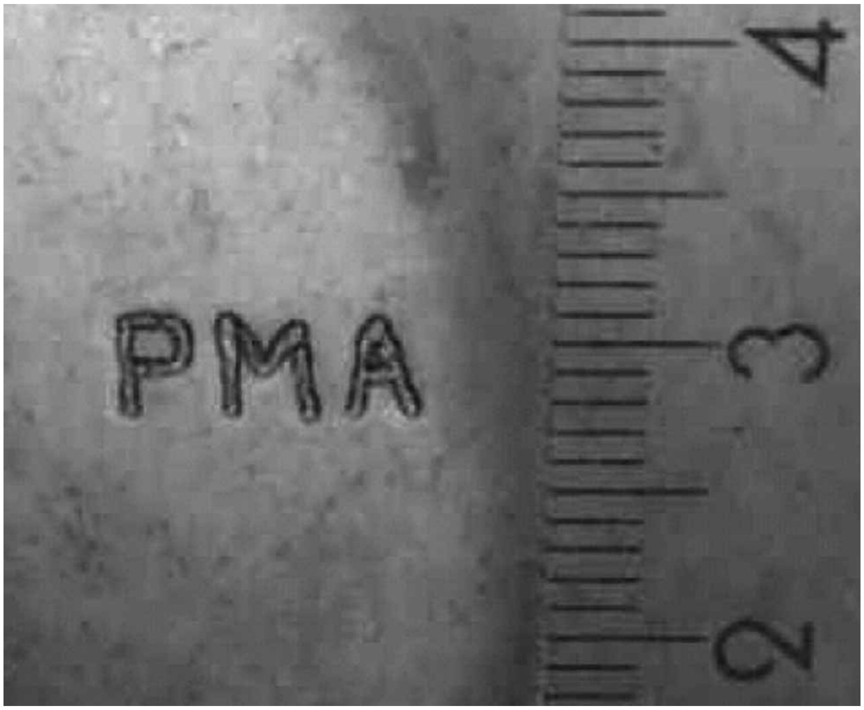


Figure 2. Handwriting-level performance achieved by using the IWI in a robot-aided laser laparoscopic procedure. The 3-mm characters cut on the apple demonstrate the feasibility of this approach.

The IWI provides the interface for the participant to use his/her writing skill by WYDIWYC, as if he/she were sketching by looking at the TV screen. The zoom in/out was executed by pushing the pen buttons. The operator could sit on the chair and triggered the laser by a foot switch similar to that in the CM setup

Participants

The 34 participants (23 males, 11 females, all free of physical disorders) were student volunteers from the Faculty of Medicine and Biomedical Science. None had any prior experience of robot-aided surgery or operative laparoscope manipulation. The participants were randomly divided into two groups: one group began with CM then switched to IM, while the other group began with IM then switched to CM, thus counterbalancing learning effects.

Experiment design

Each participant in the experiment had to accomplish three training tasks by both CM and IM. These tasks decomposed the subtasks of laparoscope navigation and laser ablation.

Task 1: Surveying and shooting exercise. This exercise consisted of hitting 15 targets 1 mm in diameter inside an area of 100 mm × 50 mm on the task paper. The subjects were advised to survey and shoot at the dots by triggering the laser in a random order. The subject was only allowed 15 shots in each trial. The completion time for firing the 15 shots and the number of successful shots for each exercise were registered. A successful shot was confirmed by inspecting the task paper to see if the laser-burn contacted the dot on the paper. Six trials were performed sequentially.

The results of Task 1 reveal the subjects' skill in surveying and aiming.

Task 2: Linear cutting exercise. This exercise consisted of tracing and cutting an equilateral upright triangle with sides of 20 mm. The subjects were advised to manipulate the laser to trace and simultaneously cut the figure by activating the laser. An error margin of 1 mm with respect to the figure lines was acceptable. The completion time and error length were recorded for each trial. The error length was estimated by inspecting the distance of the laser-burn outside the tolerance margin on the task paper. It was not necessary to complete the figure in a single stroke. Six sequential trials were performed.

The results of Task 2 were used to evaluate performance in tracing a straight line and changing direction.

Task 3: Curve cutting exercise. This exercise consisted of tracing and cutting a circle 10 mm in diameter. The subjects were advised to manipulate the laser to trace the figure and simultaneously cut it by activating the laser. As in Task 2, the completion time and error length were recorded for investigation. Six sequential trials were performed.

The results of Task 3 examined the subjects' skill in tracing curved lines.

Procedures and comparison index: the Index of Time and Error

All participants attended an introductory session on laser laparoscopic surgery. Then, the instructor gave a short explanation and demonstration of the skills involved in CM and IM. The completion time was recorded and the task paper was examined by the instructor after each trial.

The indices for evaluation were completion time and number of successful shots for Task 1, and completion time and error length for Tasks 2 and 3. The Index of Time and Error (ITE) is proposed by the authors as a way of integrating the effects of completion time and precision into a single parameter. As precision was considered more important, the corresponding weighted parameter was derived from the worst case of the individual participant performing the task over the six trials. Therefore,

Task 1: ITE = completion time + (longest time to successfully make one shot) × (number of missed shots)

Tasks 2 & 3: ITE = completion time + (error length)/(longest time to complete the figure)

Hence, the lower the ITE, the better the performance.

Statistics methods

Prism 4.0 (GraphPad Software, Inc., San Diego, CA) was applied to carry out statistical calculations. Inspection of the recorded indices demonstrated that the distribution of those values was not Gaussian. Therefore, a nonparametric paired test was employed (Wilcoxon matched pairs test) to evaluate the mean value for two manipulation setups. Secondly, the mean values for six sequential trials of each task were calculated to form the learning curve. To compare the difference between these mean values in the learning curve, one-way ANOVA was used. A one-tail paired t-test was applied to identify the differences in individual performance between CM and IM. In all these hypothesis tests, $P < 0.05$ suggested significance.

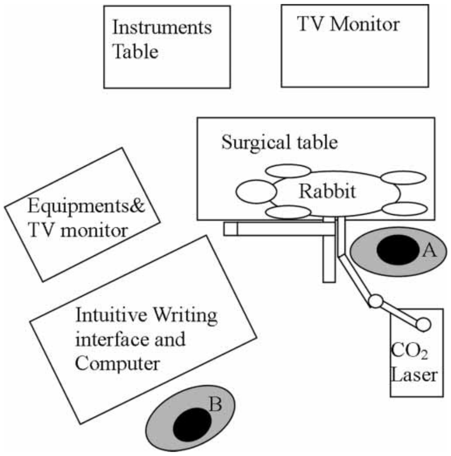


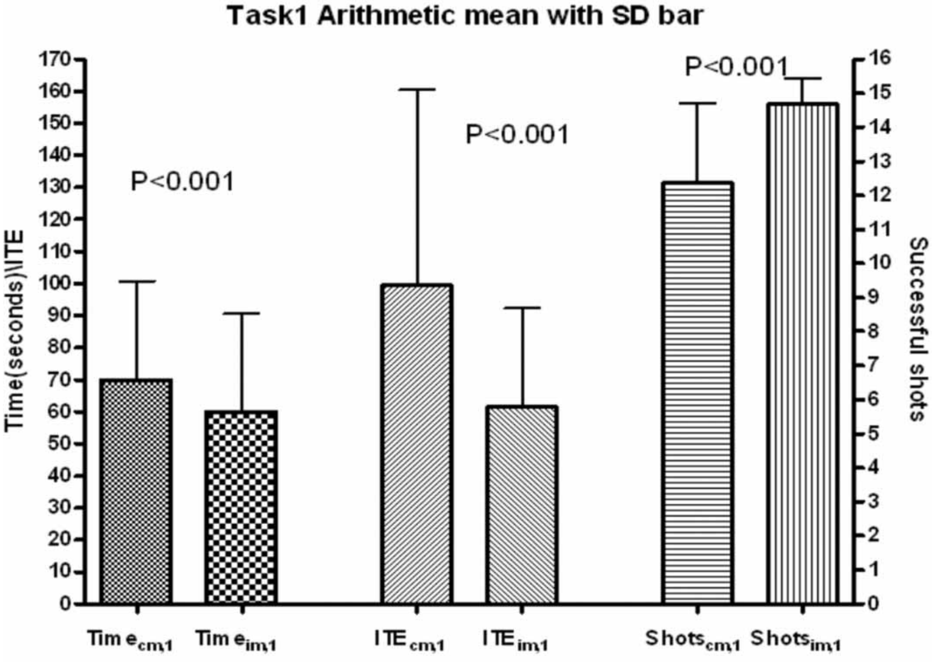
Figure 3. Overhead view of the arrangement of the animal model experiment. Surgeon A manipulated two tweezers to position the kidney and Surgeon B used the IWI to perform laser cutting.

Animal model evaluation

Two experienced urology surgeons from the University Hospital Gasthuisberg of K.U. Leuven carried out a nephrectomy aiming at the removal of the kidney in a rabbit. Minimally invasive procedures and IWI laparoscopic laser cutting were applied to separate the kidney. Figure 3 shows an overhead view of the schematic arrangement of the equipment and staff. Two TV monitors were employed to display the images from the laparoscope. The rabbit was anesthetized and arranged in a suitable position. Three trocar openings were made on the abdomen and the cavity was inflated with CO_2 gas. Surgeon A manipulated two tweezers to grasp and lift the kidney into a suitable position that exposed the cutting site to the laparoscope. Surgeon B employed the IWI to perform laser cutting throughout the whole procedure. The CO_2 laser trigger was controlled by the foot pedal. This animal model evaluation was carried out in the CST at K.U. Leuven with the approval of the ethical committee.

Results

The mean values for completion time, ITE and number of successful shots for 34 participants performing 6 trials in Task 1 are displayed in Figure 4. The two manipulation setups are displayed together for ease of comparison. The P-values of the nonparametric paired test are indicated on the figure. The left portion of the figure shows that the mean completion time for CM was significantly longer than that for IM. The right side shows that the number of successful shots was significantly higher with IM than with CM: the average for IM was 14.67 out of 15 shots, as compared to only 12.36 out of 15 for CM. The center pair of bars shows



	$Time_{cm,1}$	$Time_{im,1}$	$Shots_{cm,1}$	$Shots_{im,1}$	$ITE_{cm,1}$	$ITE_{im,1}$
Mean	69.96	59.98	12.36	14.67	99.39	61.45
Std. Deviation	30.79	30.58	2.330	0.7667	61.17	30.76
Std. Error	2.167	2.146	0.1635	0.05368	4.304	2.169

Figure 4. Results for average completion time, ITE, and number of successful shots for all participants in Task 1. P-values showed statistically significant differences between CM and IM.

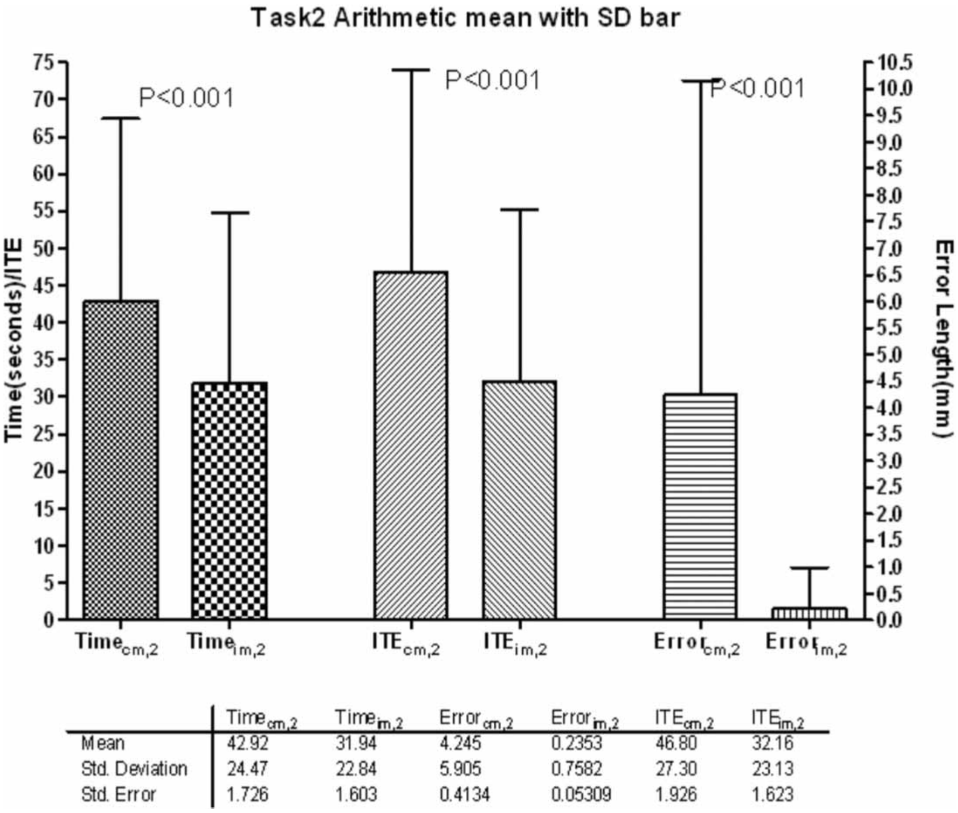
the ITEs of the two manipulation setups. These results are compatible with those for completion time and number of successful shots, but indicate a greater difference than those found for completion time alone since errors were integrated.

Figures 5 and 6 show the results for Tasks 2 and 3. The scale on the right indicates the error length in mm. On the left, the scale is in seconds and ITE units. As can be seen, the IM had a better performance than CM, with shorter completion time and error length for both tasks. The ITE shows similar results.

Since the ITE represents the combined performance of speed and precision, the learning curves for CM and IM were calculated by summing and averaging the ITEs in Tasks 1, 2 and 3 in six consecutive trials for each participant. The results for CM are shown in Figure 7. Starting with a mean ITE of 219.6 in the first trial and ending with an ITE of 151.5, the most significant ITE drop occurred between the first and second trials. The other trials confirmed a similar performance. Figure 8 illustrates the learning curve for the IM setup. Starting from an ITE value of 147.5, which was already lower than the minimum mean value for the CM trials, the best performance was achieved in the sixth trial with an ITE of 80.16. The learning continued between each trial and seemed to maintain a steady trend.

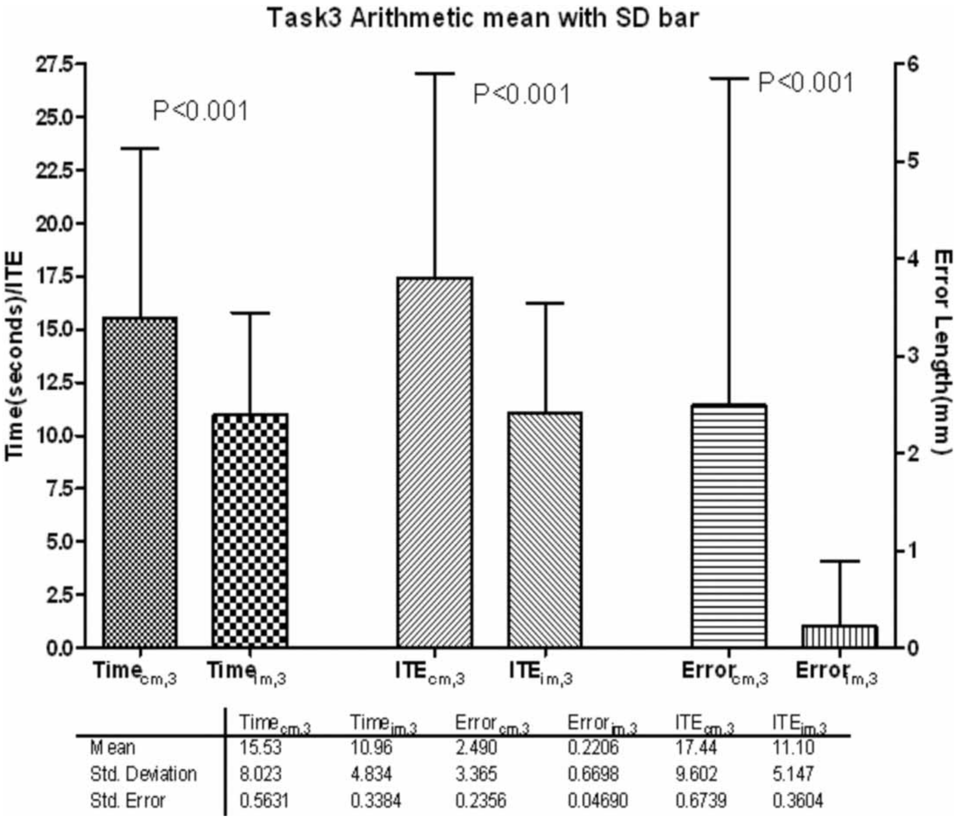
The mean values for the six trials performed by each participant using CM and IM were compared for each task. The scale of Figure 9 refers to the numbers of participants that were statistically significant. The two bars at left show the results for Task 1. Here, 25 of 34 participants performed better using IM, while only 2 performed well with CM. The other bars show the results for Task 2 (middle) and Task 3 (left). There were 19 and 21 test participants, respectively, who performed better using IM, while only 1 and 2 individuals, respectively, showed better ITE for Tasks 2 and 3.

The final test involved the performance of nephrectomy in an animal model by IWI laser cutting. The duration of the entire procedure from setting up the robot system to successful separation of the kidney was 3 hours. Within this period, the IWI was used for 45 min to perform laser cutting. All cutting in this test was performed by laser, with the ureter and artery remaining intact. The cutting was precise, stable and easy to execute. However, obstructions and collisions were encountered during the allocation and configuration of the laparoscope robot and MIS instruments. These resulted from the range of motion of the applied robot being insufficient and unsuitable for this standard procedure. An extra trocar opening was made on the rabbit abdomen to continue the experiments.



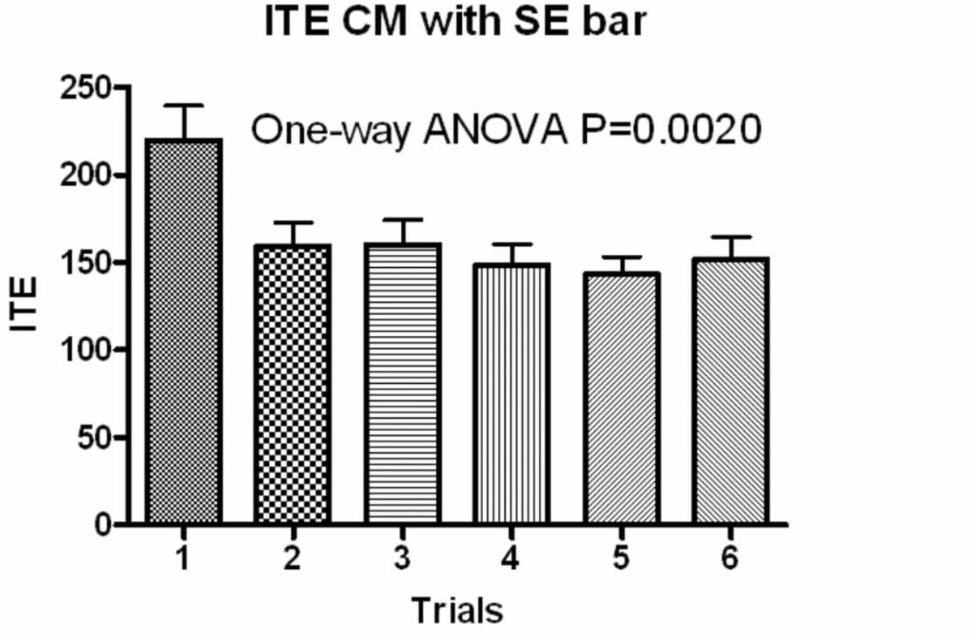
	Time$_{cm,2}$	Time$_{im,2}$	Error$_{cm,2}$	Error$_{im,2}$	ITE$_{cm,2}$	ITE$_{im,2}$
Mean	42.92	31.94	4.245	0.2353	46.80	32.16
Std. Deviation	24.47	22.84	5.905	0.7582	27.30	23.13
Std. Error	1.726	1.603	0.4134	0.05309	1.926	1.623

Figure 5. Results for average completion time, ITE, and error length for all participants in Task 2. P-values showed statistically significant differences between CM and IM.



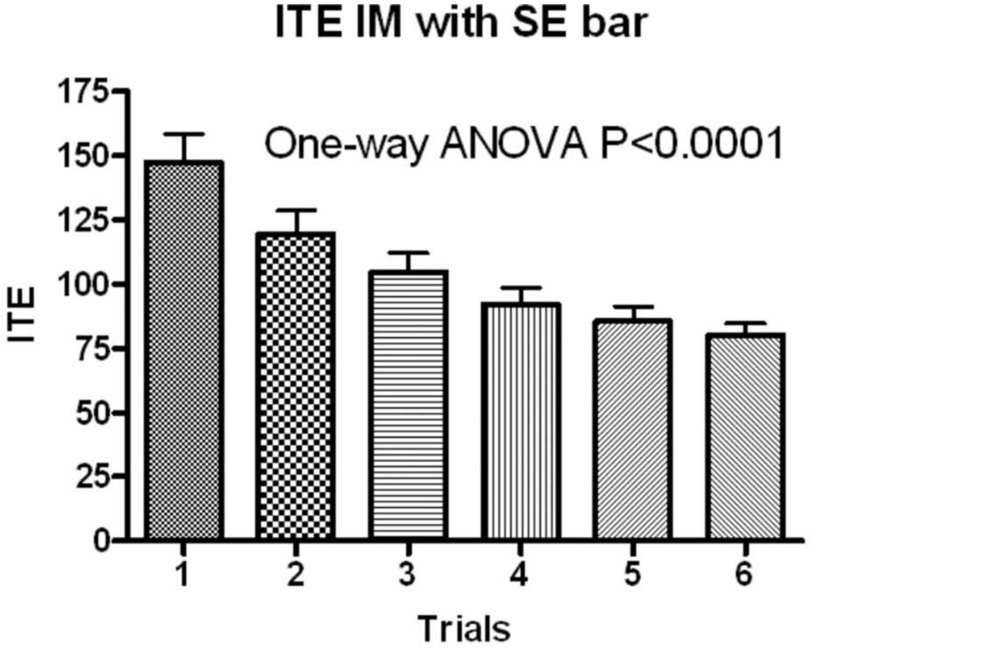
	Time$_{cm,3}$	Time$_{im,3}$	Error$_{cm,3}$	Error$_{im,3}$	ITE$_{cm,3}$	ITE$_{im,3}$
Mean	15.53	10.96	2.490	0.2206	17.44	11.10
Std. Deviation	8.023	4.834	3.365	0.6698	9.602	5.147
Std. Error	0.5631	0.3384	0.2356	0.04690	0.6739	0.3604

Figure 6. Results for average completion time, ITE, and error length for all participants in Task 3. P-values showed statistically significant differences between CM and IM.



	1	2	3	4	5	6
Mean	219.6	159.3	160.4	148.7	143.2	151.5
Std. Deviation	113.0	79.12	81.45	68.02	58.79	74.18
Std. Error	19.97	13.77	14.18	11.84	10.08	12.91

Figure 7. Mean ITEs for all participants in each trial with CM. The most significant learning occurred between the first and second trials.



	1	2	3	4	5	6
Mean	147.5	119.5	104.7	92.04	85.46	80.16
Std. Deviation	62.31	53.28	43.06	38.71	34.65	26.03
Std. Error	11.19	9.276	7.385	6.639	5.942	4.465

Figure 8. Mean ITEs for all participants in each trial with IM.

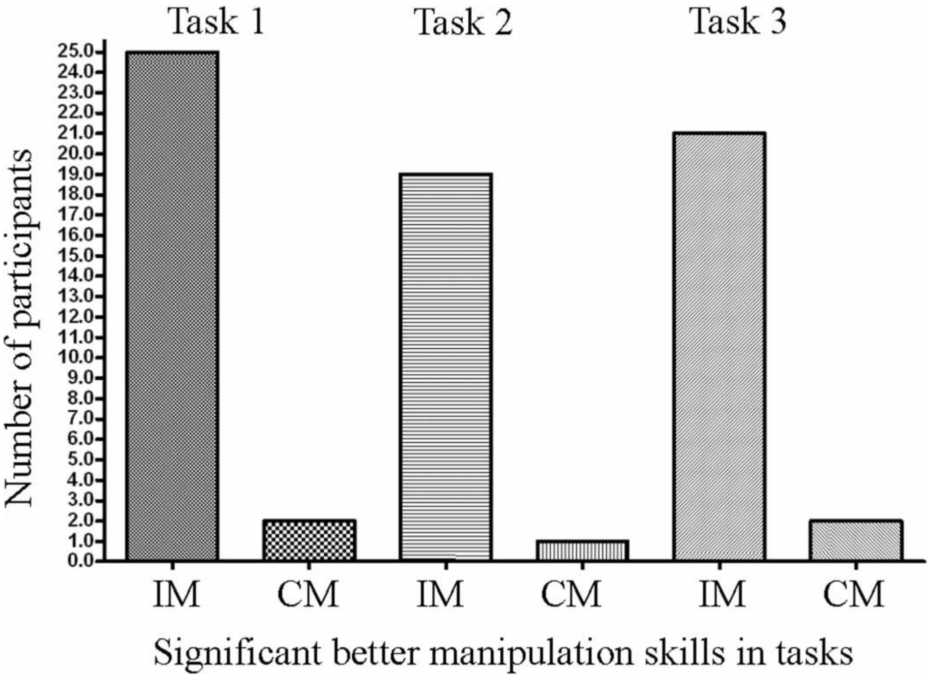


Figure 9. Number of participants with significant differences in performance for the three tasks.

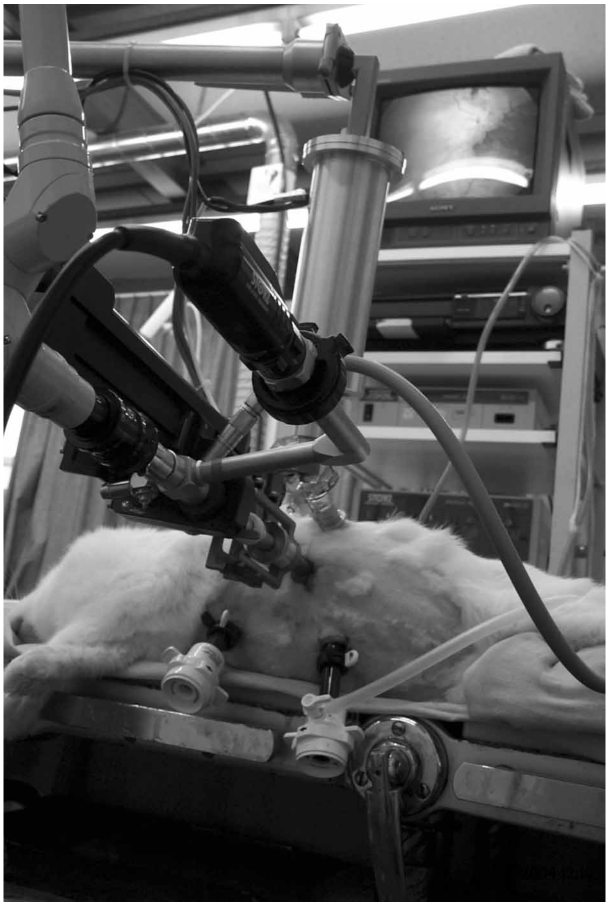


Figure 10. The surgical site in the rabbit experiment. The operative laparoscope was manipulated by the robot. Three extra trocar openings were placed on the abdomen.

Figure 10 shows the operative laparoscope being held by the robot and inserted into the rabbit. The TV screen displays the images inside the rabbit. Three extra trocar openings were placed on the rabbit's abdomen.

Discussion

The results provided quantitative information about the human performance of identical tasks using different interfaces. The IWI combined with WYDIWYC showed much better performance than direct manual handling. CO_2 laser ablation is basically a 2D procedure. Therefore, the visual perception of laser ablation was simply 2D movement and could be visually and ergonomically compared to human writing behavior. However, if patients are to benefit from the well-known advantages of MIS procedures, such as faster recovery time and shorter hospital stay, the associated drawbacks such as reduced dexterity and limited visual cues need to be counteracted. Although conventional MIS instruments provide 4 DOFs, the manual manipulation of the laparoscope results in full arm movement, which means 7-DOF inverse kinematics mapping. The opposing directions of hand movement and visual perception in MIS and the variable scale due to fulcrum effects jeopardize precise and fluent ablation.

A writing interface is simple and accurate and can play a useful role in the control of trajectory-based tasks [12]. Studies have confirmed that human handwriting is a simple 2D movement [13]. Certainly, this

2D writing movement would be appropriate and sufficient to control the 2D laser ablation. The IWI manipulation is an individual skill, and hence both setups were compared for each participant in the study. More than half of the participants showed better performance when using IM, while only a few participants performed well with CM.

The ITE defined in this research took completion time and error into account. It can be interpreted as a performance index that integrates speed and precision. These two parameters represent the two basic surgical technical skills in laser laparoscopic procedures. The weighted parameter that used the worst performance of the individual participant emphasized the importance of precision in surgery. The laser ablation being executed only on paper, it was observed that the participants were somewhat unconsciously treating the tasks as a game instead of an operative procedure. The oral instruction, as well as the intentional weighted parameter, encouraged the participants to take their role of surgeon seriously.

The tasks described, together with the ITE evaluation tool, have great potential for application in the assessment of surgical technical skills in non-contact laser laparoscopic procedures. With a selectively weighted parameter, the ITE successfully represents the performance differences between CM and IM. For assessment purposes, the 75% decision-making component was taken over by the designed tasks, which disintegrated the 25% dexterity component into surveying, aiming and shooting, and continuous linear and curvature tracing and cutting abilities. With no additional expenditure or implementation in motion analysis or virtual reality equipment and software, the ITE was shown to be a reliable and valid parameter for revealing surgical performance in this kind of procedure.

The animal model experiment demonstrated the application of laser laparoscopic cutting in nephrectomy. The stability, precision and ease of use of the IWI gained approval from the surgeon performing the procedure. However, lack of prior experience and adaptation to the new setup and robotic surgery prolonged the preparation time. The assistant's technical skill in grasping and lifting the kidney also affected the recorded duration of laser cutting. The main problems encountered during the try-out were basically related to the robot hardware used. Its limited range of motion and hanging configuration constrained the surgical space. A second hole for the laparoscope was created to allow easier orientation of the robot, but obstructions and collisions occurred between the instruments and the robot and hanging frame. The applied robot has a fixed trocar center of rotation and 4 DOFs identical to those of MIS instruments, allowing simple and easy implementation and control by the IWI. However, the design and hanging frame seemed unsuitable and impractical for this type of surgery. When aiming at improving the restricted human surgeon's skills in surgical practice, the tradeoffs and compromises should be taken into account. A valid, feasible and reliable assessment that incorporates decision-making is also necessary [14] to compare the differences and to improve the surgical quality to the best possible level.

The new IWI interface definitely improved the human skills in current laser laparoscopic procedures by taking advantage of familiar writing behaviors. An assessment index ITE was proposed and applied to demonstrate differences in clinical performance. As compared with manual manipulations, IWI manipulation performance was excellent in terms of both speed and precision. Taken together with its flexibility of implementation and ease of use, these results show that the IWI can be considered an appropriate interface concept for laser laparoscopic surgery. However, the animal model evaluation revealed the problems encountered when robotics are applied in a realistic surgical environment.

Acknowledgments

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