33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Comparative Evaluation of User Interfaces for Robot-Assisted Laser Phonomicrosurgery

Giulio Dagnino, Leonardo S. Mattos, Gabriele Becattini, Massimo Dellepiane, and Darwin G. Caldwell

Abstract— **This research investigates the impact of three different control devices and two visualization methods on the precision, safety and ergonomics of a new medical robotic system prototype for assistive laser phonomicrosurgery. This system allows the user to remotely control the surgical laser beam using either a flight simulator type joystick, a joypad, or a pen display system in order to improve the traditional surgical setup composed by a mechanical micromanipulator coupled with a surgical microscope. The experimental setup and protocol followed to obtain quantitative performance data from the control devices tested are fully described here. This includes sets of path following evaluation experiments conducted with ten subjects with different skills, for a total of 700 trials. The data analysis method and experimental results are also presented, demonstrating an average 45% error reduction when using the joypad and up to 60% error reduction when using the pen display system versus the standard phonomicrosurgery setup. These results demonstrate the new system can provide important improvements in terms of surgical precision, ergonomics and safety. In addition, the evaluation method presented here is shown to support an objective selection of control devices for this application.**

I. Introduction

The larynx is a complex organ with a multi-functional nature. It is involved, for example, in deglutition (swallowing), respiration (breathing), and phonation (voice production) [1]. As a result, a broad spectrum of disorders is associated with the larynx [2]. Laser phonomicrosurgery, which involves the use of a CO_2 surgical laser to perform meticulous operations on the vocal folds, is one example.

Laser phonomicrosurgery requires significant psychomotor skills [3] and presents many challenges to surgeons, including: poor visualization; difficult access; and a comparatively large operative distance of 400 mm. In addition, ergonomics, scalability, and the anatomically small nature of the vocal folds all combine to make these procedures even more challenging [4].

Currently, the prevailing user interface for aiming the CO_2 laser during these surgeries is the manual micromanipulator coupled with a surgical microscope [5] (see Fig. 1.A). This device allows accurate laser aiming but is prone to errors resulting from inexperience and ergonomic factors [4]. Clinicians who work with this system have to be skilled and experienced. Unfortunately, it is not an easy instrument to master and the surgeon training period can take years to complete.

These challenges and the need to improve laser phonomicrosurgeries have recently spawned new research and innovations in this area, both at the academia and industry levels. For example, Lumenis Ltd. (Yokneam, Israel) has created the Acupulse CO_2 Laser, which couples a computer controlled laser scanner with a computerized system that automates parameter selection for different laser treatments [6]. In addition, Solares *et al.* and Desai *et al.* have reported on laryngeal surgeries using a flexible CO_2 laser fiber coupled to the daVinci Surgical Robot (Intuitive Surgical Inc., Sunnyvale, CA, USA) [7], [8]. Giallo *et al.*, on the other hand, proposed a joystick-controlled surgical system based on the motorization of a traditional manual laser micromanipulator [4]. Finally, the Italian Institute of Technology (IIT) developed an assistive laser phonomicrosurgery system (Fig. 1.B) based on a new motorized laser micromanipulator and teleoperated surgical control from a computer station [9].

These new technologies aim at providing better controllability, precision, safety and ergonomics to laser phonomicrosurgery systems. Together with other surgical techniques, they form competing modalities for laser laryngeal treatment. However, there's currently a lack of control trials to support the selection of a particular approach, which makes this decision "dependent upon factors such as patient's preference, available resources, cost of treatment, established local protocols, surgeon's experience and skills rather than evidence based medicine alone" [10].

Fig. 1. Laser aiming systems: (A) traditional phonomicrosurgery setup: mechanical micromanipulator (UniMax® Micromanipulator by Laser Engineering, Nashville, TN, USA) coupled with a surgical microscope (picture copied from [4]); (B) IIT's system: computer-controlled motorized micromanipulator coupled with surgical microscope.

Manuscript received March 25, 2011.

G. Dagnino is with the Advanced Robotics Dept., Italian Institute of Technology, Genoa, Italy (corresponding author: phone: +39 010 71781213; fax: +39-010-720321; e-mail: giulio.dagnino@iit.it).

L. S. Mattos, G. Becattini and D. G. Caldwell are with the Advanced Robotics Dept., Italian Institute of Technology, Genoa, Italy (e-mail: leonardo.demattos@iit.it, gabriele.becattini@iit.it, darwin.caldwell@iit.it).

M. Dellepiane is with the ENT Dept., UniGe, Genoa, Italy (e-mail: massimo.dellepiane@tiscali.it).

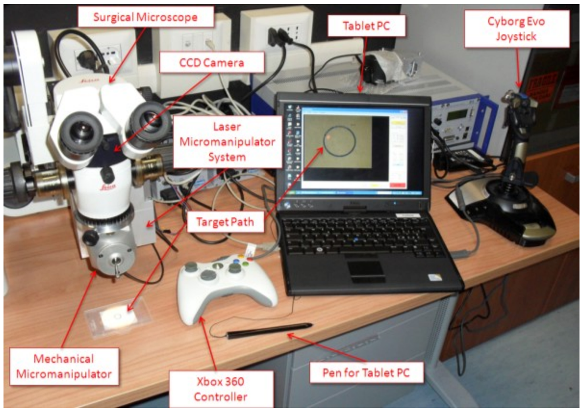

Fig. 2. Experimental setup: the motorized laser micromanipulator system is attached to surgical microscope and real-time video from the microscope's camera is shown on laptop screen. The four control devices tested are shown.

The preceding affirmation is also valid for the types of control devices used in robot-assisted laser microsurgeries, i.e., there's a lack of data to support the choice of user interface for these procedures. Therefore, this research aims at establishing metrics for evaluating user interfaces for medical robotic systems in terms of their precision, safety, user training period, and ergonomics.

In this paper, three evaluation metrics are defined to compare user interface devices in the context of robot-assisted laser phonomicrosurgery: trajectory following Root-Mean-Square-Error (RMSE), Time Employed to Complete Task (TECT) and Maximum Error (ME). Here, these metrics are used to evaluate three different control devices and two visualization methods using the IIT's system. These include: a joystick, a joypad, and a pen display as control devices; and a microscope and a computer display as visualization systems. Experiments also include trials with a traditional microscope-micromanipulator laser phonomicrosurgery system, which are used to define a baseline for performance comparisons.

This paper starts with a description of the experimental setup and protocol followed to obtain quantitative performance data from the user interface devices tested. Then, the data analysis method employed and experimental results from a total of 700 trials conducted with 10 different

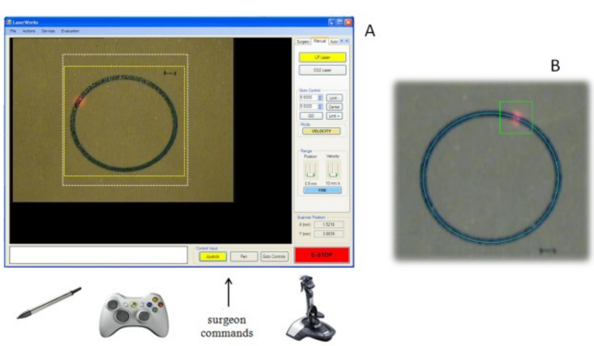

Fig. 3. A: control devices, GUI and camera view during experiment. B: the laser spot (red) tracking on the target circle line (blue line). Custom software tracks the laser to obtain laser path and target coordinates.

subjects are presented. Finally, these results are discussed, showing that the evaluation method and metrics established here can indeed support an objective selection of user interface devices.

II. Materials and Methods

A. Experimental Setup

Experiments conducted during this research were based on the laser phonomicrosurgery system developed by the IIT [9]. This system is shown in shown in Fig. 2, along with the user interface devices tested. The experimental setup included: a low-power red visible laser (Global Laser Cameo 1260); the IIT's motorized laser micromanipulator; one analog joystick (Saitek Cyborg Evo Force); one joypad (Microsoft Xbox 360 controller); one Tablet PC (Dell Latitude XT2); one surgical microscope with CCD camera (Leica M651); and the IIT's system control software, which allows control of the laser on the surgical field by means of a range of controllers (Fig. 3.A).

TABLE I
Users Information And Experience

User	U1	U2	U3	U4	U5*	U6	U7	U8*	U9*	U10
Age	28	27	26	28	50	28	28	33	27	35
Sex	M	F	M	M	M	M	M	M	F	M
Hand	R	R	R	R	R	R	R	R	R	R
EMS	2	2	3	1	5	3	1	4	4	5
EMP	1	1	4	1	4	3	1	2	4	5
ETOP	1	1	3	1	4	3	1	2	4	5
EVG	4	1	4	4	1	4	3	5	4	3

Information about users collected before starting the experiments through an auto-evaluation questionnaire. Experience level scale is from 1 (none) to 5 (very good). EMS = experience with microscope; EMP = experience with micromanipulation; ETOP = experience with teleoperation; EVG = experience with videogame. * ENT surgeon.

B. Experiment description

The experiment designed to collect quantitative data about the precision, safety, user training period and ergonomics of the user interfaces tested consisted of a trajectory following task. Here, the experimental process was divided in two steps consisting of:

1) Trials under manual control

These were performed to collect data from the control devices (joystick, joypad, pen display, and mechanical laser micromanipulator), and visualization methods (computer display or directly through the microscope). In this case, test subjects were asked to move the laser beam along a target trajectory using the different control devices, and videos of each trial were recorded for later analysis. The target path used for the experiments consisted of a circle with 8.5 mm in diameter printed with a 0.5 mm line width on a piece of white paper. We chose a circle as target path because it is related to the real surgical application: laser surgery of vocal folds requires several circular (or arc) ablation paths. This target was set under the surgical microscope, which was set to a 16x magnification. The laser used for these trials produced a relatively large spot on the target area, which measured approximately 1 mm in diameter.

In this research, experiments were conducted with 10 subjects with different backgrounds, as described in Table I. Three of them were ENT surgeons. After a familiarization phase with the setup, which lasted about 1 minute, each one of them was asked to perform 10 sets of experiments with each control device and visualization modality tested, adding up to a total of 700 trajectory following trials: 10 times with mechanical micromanipulator and microscope view (MM); 10 times with mechanical micromanipulator and pc display view (MD); 10 times with joystick and microscope view (JM); 10 times with joystick and pc display view (JD); 10 times with pen and pc display view (PD); 10 times with joypad and microscope (XBM); 10 times with joypad and display (XBD).

The order of the trials was randomized. When the users were using the pen, the laser spot was well visible on the pc display and used as visual feedback to trace the circle.

At the end of the experiments each subject also completed a questionnaire designed to collect data about their personal ratings towards of the system, the control devices, the visualization modalities and ergonomics.

2) *Data analysis*

Data analysis was performed offline to obtain performance metrics (RMSE and TECT) for each trajectory following experiment performed. This was based on custom video processing software designed to extract the path followed by the laser spot and the target trajectory coordinates from the recorded experiment videos, as shown in Fig. 3.B. This data was then processed using a Matlab code created to compute the RMSE on the trajectory following task, the time to complete the task, the maximum error observed, and graph the results (Fig. 4).

Calculation of RMSE was performed according the following equations:

$$Error(i) = \min\_dist(A_i, T) \qquad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=0}^{n}\{[Error(i)]^2\}}{n}} \qquad (2)$$

where A_i is the actual aiming point and T is the target path. At each A_i the targeting error is assumed to be the minimum distance from that point to the target path.

III. Results

We found that there was a significant difference in the performance depending on the control and view mode adopted. As depicted in Fig. 5.A, the lowest average RMSE was obtained using the pen on the tablet pc. The worst result observed was with the joystick and visualization through the computer display. It was also noticed that when using the mechanical micromanipulator, the joystick, or the joypad, coupled with microscope view, the RMSE was lower. Results from the TECT measurements are presented in Fig. 5.B. Similarly to average RMSE, the best result in this case was obtained with the pen on tablet pc and the worst with the joystick.

Furthermore, a learning trend analysis shows that the trend lines of average RMSE and TECT decreasing over the user trials, meaning that they were becoming more familiar with the system and more precise at each trial. It is worth to notice that the slopes of the joystick and the joypad average RMSE trend lines are steeper than the mechanical micromanipulator ones, indicating that these devices could allow for better results if users perform more training.

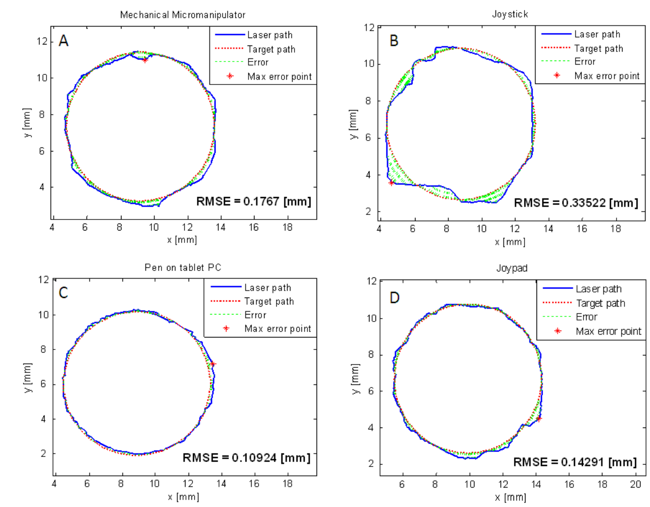

Fig. 4. Graphs of laser path over the target path with different control devices. A: mechanical micromanipulator; B: joystick; C: pen display; D:

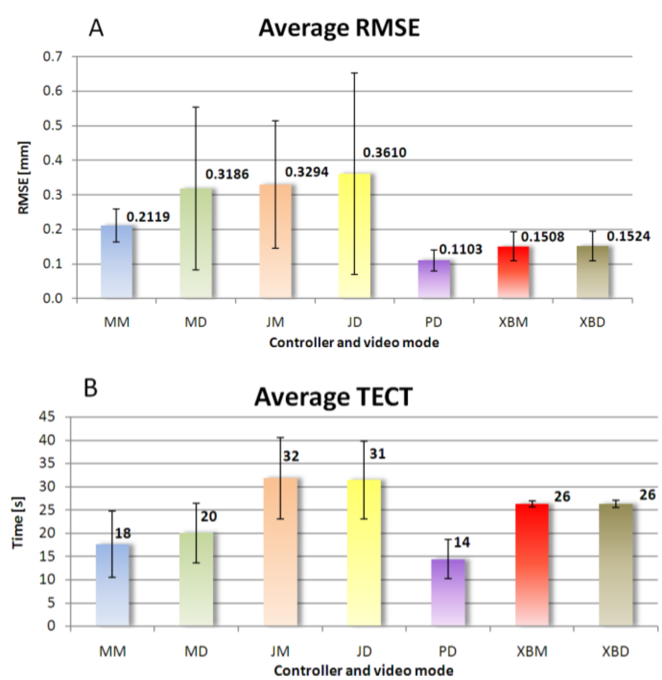

Fig. 5. A: average RMSE for each control and vision mode. B: average time employed to complete the task. The best scores are with pen and display in both cases. All hypothesis were tested using an alpha level of 0.05.

In Table II, data about ME are reported: the pen on tablet pc gives the smallest ME followed by joypad.

Data collected during the experiments agree with the data from the evaluation questionnaires. All subjects expressed preference towards the pen display device and found it easy to use, controllable, precise and very ergonomic. They also preferred the joypad over the joystick, expressing that the joystick is difficult to control and imprecise. On the other hand, the mechanical manipulator was preferred over the joystick, but considered inferior to both the joypad and the pen display system. In addition, subjects preferred the PC display over the microscope for visualization, adding that the display is less tiring for the eyes and more ergonomic.

TABLE II
MAXIMUM ERRORS FROM PATH FOLLOWING EXPERIMENTS

Control Mode	Average Max Error	Absolute Max Error
MM	0.3850 ± 0.1955 mm	1.6194 mm
MD	1.2041 ± 0.8124 mm	12.3954 mm
JM	0.8322 ± 0.3374 mm	3.6926 mm
JD	1.2166 ± 0.6356 mm	12.8878 mm
XBM	0.1700 ± 0.0659 mm	0.5280 mm
XBD	0.1641 ± 0.0682 mm	0.6300 mm
PD	0.0792 ± 0.0282 mm	0.3186 mm

IV. DISCUSSION

The choice of proper controller is important and influential when teleoperated surgery is performed. This aspect is very important for the safety of patient and surgeon comfort during operation. We found that the best control mode is pen on tablet PC, because of its high precision and ease of use. Both questionnaires answers and experimental data indicate pen and pc display as the better configuration in terms of precision, ergonomics and ease of use. All ten users expressed their enthusiasm in the use of this control as a very intuitive control mode. They all had their best performance in terms of precision (average RMSE) and time employed to complete the task (average) with the pen display system.

Users also preferred the mechanical micromanipulator over the joystick, whereas joypad was preferred over both of these other two devices. This was also confirmed by experimental data: considering the overall average path following RMSE obtained with the classic mechanical micromanipulator as a benchmark, we found that the use of the joystick increased that error by about 30%, while the joypad and the pen on tablet PC respectively reduced that error by approximately 45% and 60%.

The joystick was considered difficult and frustrating by the users: the laser spot micro-movements depend on arm and wrist displacements, which are not very precise. The use of fingers for laser aiming (e.g. with joypad) proved to be a good improvement for system precision and ergonomics.

ME analysis resulted in an interesting way to evaluate the control devices in terms of safety: phonomicrosurgery requires very precise and controlled laser aiming, and deviations from the target can negatively impact the surgical outcome. Table II shows that both the mechanical micromanipulator and the joystick presented considerable deviations from the target, probably due to their intrinsic ergonomic issues. These deviations increase when the mechanical micromanipulator and the joystick are coupled with PC display view. The high absolute ME values reported with MD and JD are both from the unique user who had seriously problem with the PC display view.

Another important aspect of teleoperated surgery we wanted to investigate was the visualization mode. Here we tested visualization through surgical microscope (standard mode) and a pc display: nine out of ten users preferred this last system. Nonetheless, experimental data showed that the average RMSE increased when the pc display was used: this was probably due to background skills of users. Indeed users who were very good videogamers and/or had a good familiarization with the new surgical system (four users) also had a better result with the joystick and the display than with the microscope. Only one user had a better performance with micromanipulator and display than with microscope.

Finally, these results demonstrate the evaluation protocol employed here is able to support an objective selection of control devices for laser microsurgery. The new knowledge generated by this research will be used to guide further development of the IIT's medical robotic system for laser phonomicrosurgeries, helping to maximize its impact in terms of precision, ergonomics and safety.

Trajectory following experiments will be standardized so that a comparison between different systems will be possible. The final stage of this research will focus on moving this new technology to the operating room. This will be done through safety certifications and clinical trials.

REFERENCES

[1] M. Remacle and H. E. Eckel, *Surgery of Larynx and Trachea.* Berlin: Springer, 2010.

[2] A. C. Rosen and C. B. Simpson, *Operative techniques in laryngology*. Berlin: Springer, 2008.

[3] S. M. Zeitels, *Atlas of phonomicrosurgery and other endolaryngeal procedures for benign and malignant disease*. San Diego, Calif.: Singular, 2001.

[4] J. F. Giallo, "A Medical Robotic System for Laser Phonomicrosurgery" PhD Dissertation, *North Carolina State University*, 2008.

[5] M. Remacle, and V. Oswal, *Principles and practice of lasers in otolaryngology and head and neck surgery.* The Hague, The Netherlands, Kugler Publications, 2002.

[6] (Brochure Online) Lumenis Inc., "Acupulse CO_2 Laser," Available: www.surgical.lumenis.com/pdf/AcuPulse_Brochure.pdf.

[7] C. A. Solares and M. Strome, "Robot-Assisted CO_2 Laser Supraglottic Laryngectomy: Experimental and Clinical Data" *Laryngoscope* vol. 117(5):817-820, May 2007.

[8] S. C. Desai, C. K. Sung, D. W. Jang and E. M. Genden, "Transoral Robotic Surgery Using a Carbon Dioxide Flexible Laser for Tumors of the Upper Aerodigestive Tract". *Laryngoscope* vol. 118(12):2187-2189, December 2008.

[9] L. S. Mattos, D. G. Caldwell, M. Dellepiane and E. Grant, "Design and control of a robotic system for assistive laser phonomicrosurgery". *Proceedings of the 32nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, EMBC 2010, September 2010.

[10] S. Chawla and A. S. Carney, "Organ preservation surgery for laryngeal cancer" *Head & Neck Oncology* 1:12, May 2009.