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Enhanced Computer-Assisted Laser Microsurgeries with a "Virtual Microscope" based surgical system

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***Abstract*—Ergonomic and human-centered approaches are increasingly important in the design of surgeon-machine interfaces. In the case of microsurgeries, the procedures suffer from susceptibility to variation in surgeon skill and equipment characteristics. This paper presents a novel, computer-assisted surgical interface for laser-based microsurgeries, called the "μRALP Surgical System". With the system, surgeries can be performed with improved safety and precision using a three-part architecture: (i) a 3D viewer device providing stereoscopic visualization; (ii) a graphics stylus that controls a motorized micromanipulator for laser aiming and activation; and (iii) a configuration interface allowing system setup and modifications in real-time. The system combines the advantages of a computer-assisted platform while respecting the visualization and manipulation requirements of a microsurgical procedure. The features include intraoperative planning for automatic laser incisions and ablations as well as safety regions based on virtual overlays in the surgeon's field-of-view. A comparative evaluation of the proposed system against the traditional system points to the clear superiority of the new interface. The quantitative comparison shows that the proposed interface is safer, more precise, and better controlled. The qualitative comparison demonstrates that the interface is easier to use, easier to learn, and has a minimal training requirement. The technological advances presented here shall lead to enhanced interfaces, increasing the capacity of surgical systems through user-centered design approaches.**

***Index Terms*—Computer-assisted surgery, virtual microscope, stylus-based manipulation, laser microsurgeries.**

I. Introduction

Surgical interventions require a high degree of capability (ability to carry out complex surgical tasks), efficiency (executing surgeries with minimal resources), and safety (for both the patient and the surgeon). Through increased task precision, reduced tremor in gestures, timely execution of repetitive tasks, among other features, surgeons see robot-assisted surgeries as a key part of the modern surgical infrastructure [1]. Yet, the quality and efficiency of the surgical outcome depends on the characteristics of the robotic surgical equipment itself [2]. This is especially true in the case of microsurgeries, such as phonomicrosurgery, where the surgical areas, within which the surgeons have to dissect and treat the abnormalities, are small (the order of mm). The finer the surgical procedure, the greater is the dependency on dexterity and skill of the surgeon. These, in turn, depend on the controllability and precision of the surgical system. The surgeon may require to undergo a long training process on the robotic surgical system to achieve the requisite quality of surgical outcome [1], [2].

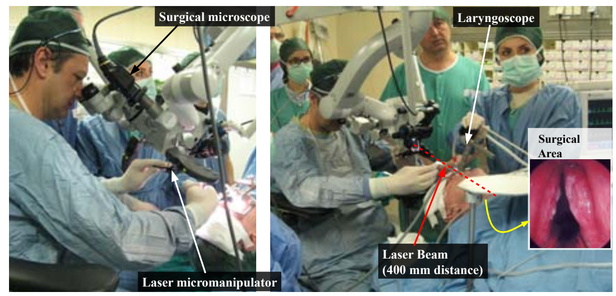

Fig. 1. Example of the Laser Phonomicrosurgery surgical system.

Laser Phonomicrosurgery (LP) is a state-of-the-art microsurgical procedure for the treatment of vocal cord abnormalities. The traditional LP system currently used in the Operating Room (OR) (Fig. 1) consists of: (i) a surgical microscope providing visualization; (ii) a mechanical micromanipulator used to manually aim the laser beam; and (iii) a separate footswitch to activate the laser. Evidently, such a setup requires the surgeon to have high psycho-motor skills to overcome challenges of hand-eye-foot coordination, poor ergonomics, sub-optimal visualization, and difficult surgical site access at a large distance ($400mm$), among others [3]. Several improvements have been proposed to this setup, both commercial and research-based. One of the main improvements is the ability to execute high-quality incisions with pre-programmed patterns using motorized laser scanning mirrors [4], [5]. Commercially available devices also offer such enhancements: the *Lumenis AcuBlade*, the *KLS Martin SoftScan*, and the *DEKA HiScan*. However, these devices have done little to enhance the surgeon's usage experience, since the poor ergonomics and discomfort still persist. Figure 1 shows the state-of-the-art surgical setup in LP, using the AcuBlade system. Research has found the system to not only have inferior precision and repeatability, but also to be difficult to use and learn [3], [6].

This paper presents a redesign of the laser-based microsurgical interface that replaces the traditional setup with a novel, computer-assisted surgical system. The main components of the new robot-assisted microsurgical system are: (i) a 3D viewer device acting as the virtual microscope providing the surgeon with real-time, high-definition (HD), stereoscopic visualization of the surgical area. The 3D viewer is held-in-place for the surgeon to look through, similar to a surgical microscope; (ii) a graphics stylus which controls a motorized laser micromanipulator, allowing the surgeon to perform operations with greater precision; and (iii) a separate touch-screen monitor providing an interface for system configuration, surgical work-flow definition, and supplementary visualization in the OR. As is observed, this setup combines the features of any computer-assisted system (i.e., improved precision, safety and controllability) with the visualization and configuration requirements of a delicate microsurgical procedure. The features and benefits include: (i) the augmentation of surgeon skills through scaling of gestures and magnified visualization; (ii) Elimination of extensive equipment training due to the intuitive stylus-based manipulation; and (iii) the possibility of intraoperative planning and virtual overlays to assist in the surgeon during surgery. The concept is shown in Fig. 2.

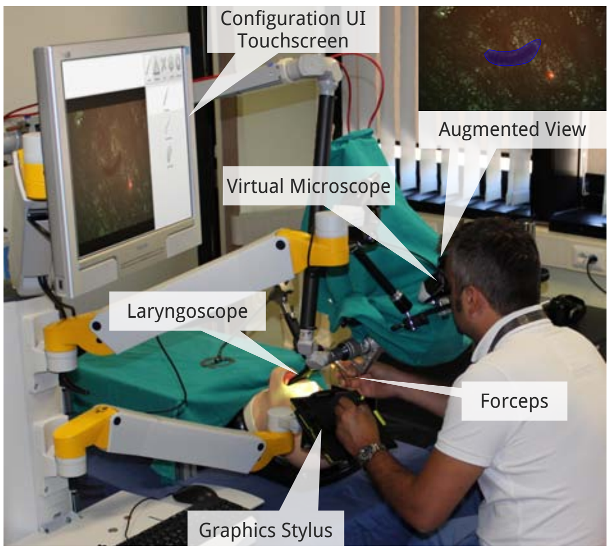

Fig. 2. The μRALP Surgical System concept.

II. Related Work

The recognition that interfaces (and human factors) play a major role in the success and quality of laser-based microsurgeries has driven recent research into the use of different surgical systems for laryngeal laser procedures. Solares and Strome [7] and Desai *et al.* [8] demonstrated the utility of the da Vinci system [9] in microsurgeries by coupling the new CO_2 fiber laser to one of its tool tips. Their research emphasized the need for a relook at current laser aiming precision, resolution and scanning capabilities [8]. The work of Giallo [10], with motorized micromanipulator aiming control, suffered from calibration and scaling difficulties and poor reproducibility. Tang *et al.* [11] proposed a writing-based interface for controlling laser aiming in robot-assisted laser laparoscopy. Their research demonstrated the positive impact a more intuitive surgeon interface can have on the accuracy of incisions, the overall stability, and training requirements. Similarly, Reinisch *et al.* [12] demonstrated the control of a laser ablation system via a graphical user interface that allowed the selection of aiming points within a screenshot of the target area.

LP is the focus of novel research at the Istituto Italiano di Tecnologia (IIT), in the context of the European project - μRALP. Mattos *et al.* [6] presented a novel surgeon interface design, called the "virtual scalpel" system. This system replaces the manual micromanipulator interface with a motorized one, which is controlled through a graphics stylus. A monitor with live video of the surgical area provides visualization to the surgeon. The immediate advantage was that both aiming and activation of the laser were controlled by the stylus [3], [6]. Yet, the key limitations noted were: (i) the lack of stereoscopic visualization of the surgical area, and (ii) the sub-optimal location of the interface (away from the patient). This restricted the surgeon's ability to gauge the surgical margins and constrained the in-surgery tissue manipulation capability.

The research in this paper continues the improvement into the ergonomic and objective aspects of the LP surgical interface design. The introduced combination of motorized manipulation and 3D visualization makes full use of the surgeons' skills along with augmenting the surgeon's field-of-view with real-time planning and safety features. The technology introduced in this paper can be adapted to the larger domain of laser surgeries, improving the state-of-the-art in robot-assisted surgical interfaces.

III. The μRALP Surgical System concept

Through close interactions with the surgeons and their subjective and analytical feedback [3], two aspects were understood to be key in the surgeons' preferences in technology for microsurgeries:

1) Proximity to the patient: required for fine adjustments and tissue manipulation to be carried out during the surgery.
2) Enhanced visualization: required to better understand the surgical margins and planning of the surgery.

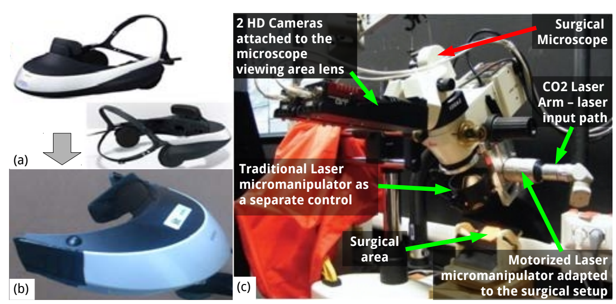

Fig. 3. Current hardware setup of the μRALP Surgical System.
(a) SONY HMZ-T2 3D Viewer; (b) Modified 3D Viewer as *Virtual Microscope*; (c) The surgical setup with the HD cameras and manipulator attached to the surgical microscope.

The μRALP system is designed to incorporate the above aspects in the system while providing all the important features of a computer-assisted surgical system. The motivation was to allow surgeons the precise aiming control provided by motorized laser manipulation, along with the ergonomic advantages of using a graphics stylus, over the real-time 3D visualization of the surgical site. Following are the main elements of the new system:

1) Motorized Micromanipulator: This component, introduced in [13], was designed to be attached to the traditional LP equipment and is installed on its laser entry port. The final device, based on a fast steering tip/tilt mirror (FSM), is fully computer-controlled and able to realize accurate scanning motions at frequencies up to $200Hz$. It provides a $4\mu m$ positioning accuracy and a $40mm$ x $40mm$ range at the typical $400mm$ operating distance [13]. This allows the physician to realize long cuts with precision, uniformity, and consistency.
2) Graphics Stylus with Tablet: The *WACOM Bamboo Pen and Touch* tablet was chosen for laser aiming control and as a mouse input for intraoperative planning and system configuration (Fig. 6 - Top Left). It can be controlled using a stylus pen or finger touch. The stylus touching the tablet activates the laser.
3) Virtual Microscope: This component preserves the close proximity of the surgeon with the patient while providing real-time HD stereoscopic visualization of the surgical area. The configuration for this component is a two-tier structure:
   a) Stereoscopic video acquisition is realized through two HD cameras (*Prosilica GT1910 GigE Vision* - $1080p$) attached to the surgical microscope, as shown in Fig. 3c.
   b) A 3D head-mount display (*SONY HMZ-T2* - $720p$) device, suitably modified as shown in Fig. 3b, is used to display the acquired video. The device has laterally adjustable viewing lenses to adapt to different facial contours, and has a forehead rest which turns the display on/off. The device is fixed to the surgical platform with an adjustable arm (Fig. 2). This modification presents another key advantage - it does not restrict the surgeon's view to the surgical area, effectively avoiding an isolation of the surgeon from the operating room environment.
4) Configuration Interface: This component is used for system configuration, surgical work-flow definition, safety alarm messages, as well as supplementary surgical site visualization. Two important factors led to adopting a separate touchscreen interface for the configuration panel:
   a) Since the surgeon's visual field is through the virtual microscope, it was deemed unfit to crowd the visual area with configuration information.
   b) The necessity was identified to allow a surgical assistant to make the changes to the configuration settings without requiring the surgeon's intervention for it.

   Additionally, a larger screen for all the settings, messages, and the supplementary surgical area view produces less visual strain. Refer Fig. 4.

Fig. 4. Configuration Interface and representation of a surgical assistant interacting with it through a touch screen.
The information is presented on the left side of the interface and the user input areas are placed on the right side. Each category opens a specific options panel.
The assistive features are also shown overlayed on the microscope image.

This arrangement provides the following benefits: (i) the custom-designed, motorized, laser micromanipulator improves aiming accuracy; (ii) the assistive teleoperation and automation improve the precision, controllability, and safety; and (iii) the separation of the surgical and configuration interfaces decouples the two activities and allows them to be carried out independently. Additionally, as a research platform, the virtual microscope enables research into 3D surgical planning and 3D laser control.

A. System Architecture

Figure 5 shows the overall architecture of the μRALP surgical system concept. As is evident, the surgeon remains in control of the entire system, while different components of the system assist in the surgical tasks. A user interface software controls the entire system and interfaces with the various devices in the system.

The virtual microscope and the configuration interface combine to provide the key features of the system:

1) The surgeon performs the surgical tasks in the virtual microscope interface. The configuration interface allows to choose between the different task categories based on the requirement of the surgeon.

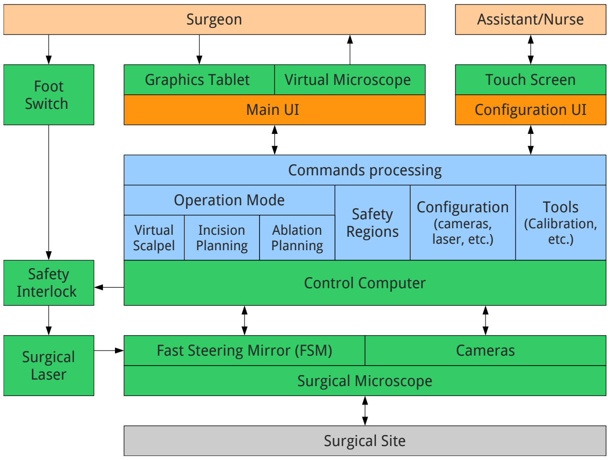

Fig. 5. The μRALP surgical system architecture.

2) Different parts of the configuration screen are allocated for different categories. These include: (i) in-surgery messages for information and alarms, (ii) different assistive features, (iii) tools for system calibration and hardware configuration, etc. The surgeon or surgical assistants can monitor and alter the different parts independently.
3) The assistive features in the surgeon's field-of-view are (Refer Fig. 4):
   a) Virtual Scalpel: Precise aiming and incision with the laser using the stylus and tablet interface.
   b) Intraoperative path-planning: The stylus can define virtual scan patterns in the surgical area. This allows incision planning for automatic execution of pre-defined paths as well as ablation planning for ablation of pre-defined regions of the surgical area.
   c) Safety region overlays: The stylus can define the regions within the surgical area where the laser is either: (i) active only inside the region (Safe area), or (ii) inactive inside the region (Dangerous area).

The high-level commands generated by the surgeon controlling the graphics stylus, or inputs from the configuration interface, are processed by the software and converted to: (i) low-level motion commands for the motorized manipulator using the calibration parameters, (ii) augmented reality overlays in the video feed, and/or (iii) system configuration change inputs. The control software, based in ROS, ensures high repeatability and consistency. The conventional footswitch and a hardware interlock are also included to provide an additional level of safety by deactivating the laser when not in use or when commanded by the software system. System calibration involves transforming the coordinates of the laser spot from image space (surgeon's display) to the coordinate system of the motorized laser micromanipulator. The procedure from [13] is adopted here - the laser spot is moved automatically to a pre-defined set of locations and at each location the stylus input locations are recorded. The calibration patterns can be pre-defined in an independent configuration file so they can be used for different magnifications, optics, input devices, and laser controllers.

IV. Experimental Validation

To demonstrate the enhanced usability and performance of the μRALP surgical system, it was compared with the traditional laser control interface, as shown in Fig. 6, Top-Left. A two-stage procedure was adopted for comparison: (i) a quantitative assessment using the trajectory following trials, introduced in [3], [14], and (ii) a qualitative assessment through a questionnaire. The combination of the two stages provided for a clear classification of the two examined surgeon interfaces. The trials were performed with 10 non-medical subjects - the subjects had no prior experience with either interfaces. The trials were performed in two sets, first using the μRALP system and then the traditional system. This sequence eliminated the possibility of any benefit for the μRALP system through learning bias.

The experiments consisted of two different tasks: (i) sets of trajectory following exercises through laser-tracing, and (ii) ablating chicken tissue through randomized dot patterns. The trajectories, randomized sets of C-curves, S-curves, and straight lines were stamped on plaster blocks for easier analysis and reproducibility. The ablation task involved ablating the tissue at pre-defined, randomized spots marked on the chicken tissue. The subjects were asked to follow the spot ablation one-by-one, in anti-clockwise direction. Both the tasks were representative of real surgical actions and allowed the assessment of the accuracy and precision of the interfaces. Figure 6 shows the experimental setup. Custom software was written to analyze the data from the experiments.

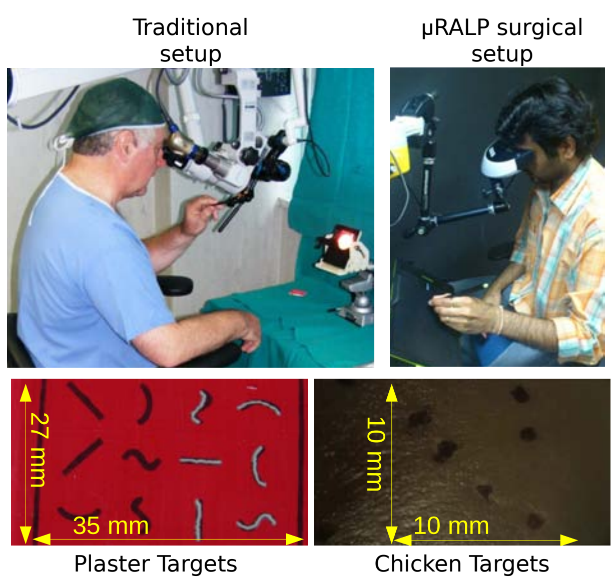

Fig. 6. Experimental Setup. The figure shows the targets used for the experimental tasks. The plaster blocks have randomized sets of trajectories and are clearly marked by the CO_2 laser. The chicken tissue are marked with randomized spots for the ablation task.

A. Quantitative Assessment

The quantitative assessment consisted of two different evaluations:

1) System Accuracy: This was assessed through the trajectory-following task on pre-defined random shapes (Fig. 6). The root-mean-square-error (RMSE) and the maximum error (Error_{max}) metrics were used for comparison (introduced in [14]). Considering the number of subjects and the number of shapes traced by each of them (6), there are 60 data points for each of the metrics in each of the conditions (traditional and μRALP). Table I summarizes the t-test analysis for the two accuracy metrics. The two conditions show a statistically significant difference in performance. The μRALP condition permits a significantly more accurate performance than the traditional condition.

- RMSE: The virtual microscope condition permits easier trajectory following with the laser than the traditional condition.
- Error_{max}: The virtual microscope condition permits better control of the laser than the traditional condition. It helps avoid large deviations from the desired trajectories.

TABLE I
COMPARISON OF AVERAGE VALUES OF THE ACCURACY METRICS (MM).

	Traditional condition		μRALP condition		t	p
	mean	sd	mean	sd		
RMSE	0.65	0.11	0.36	0.14	4.748	2e-4
Error_{max}	1.38	0.25	0.68	0.23	6.309	6e-6

The above metrics are directly related to the operational safety and efficiency of the interfaces. A high value for the RMSE gives an account of how far the laser-traced shape is from the desired shape. This implies that the laser is active in non-desired areas. In case of real surgeries, this would mean that the laser is ablating more than the desired area of the tissue, may be healthy tissue. On these parameters, the μRALP interface consistently shows closer to ideal values, much more so than the traditional interface. It is evident that users perform better with the μRALP interface in general. This aspect is also reflected in the execution time evaluation and the qualitative evaluation to follow.

2) Execution Time: To understand the effect of the two interfaces on the actual times for trial completion, the durations of the trials were recorded for both, the chicken tissue ablation task and the trajectory following task (6 shapes). The results of the t-test analysis are summarized in the Table II.

TABLE II
COMPARISON OF TIMES FOR TRIAL COMPLETION (SECONDS).

Task	Traditional condition		μRALP condition		t	p
	mean	sd	mean	sd		
Trajectory Task	7.58	2.29	4.03	1.58	3.836	1e-3
Tissue Ablation	30.50	7.12	21.60	6.42	2.936	0.008

There is a significant difference for the trial times in the two conditions. The subjects in the traditional condition take a significantly longer time to complete the trials than the subjects in the μRALP condition. This is an interesting result which shows that the μRALP condition allows the trajectory following tasks to be performed faster and more precisely than the traditional condition.

B. Qualitative Assessment

For these evaluations, the System Usability Scale (SUS) questionnaire was utilized, as described in [3]. SUS allows the evaluation of surgical technology in terms of general usability. Upon receiving the SUS questionnaire, the subject must read each statement and evaluate whether and how much he/she agrees with it. The questions are listed in Table III.

The questionnaires clearly demonstrated the different level of usability assigned by the subjects to each interface (traditional vs. μRALP). A t-test analysis showed that the difference between the SUS global scores for the two conditions was statistically significant with p = 0.0462. This implied that the subjects attributed a much higher level of overall usability to the μRALP interface (m = 82.00, sd = 8.16) than the traditional interface (m = 74.67, sd = 7.11), on a 100-point scale. This is an expected result. In general usability, the μRALP system is perceived as a device which is easier to use and adapt to surgical tasks.

TABLE III
COMPARISON OF SUS SCORES

Sr. No.	Questions	Traditional condition	μRALP condition	% betterment for μRALP on Traditional
		mean	mean	
1.	I think that I would like to use this system frequently.	75.00	75.00	0.00
2.	I found the system unnecessarily complex	73.33	91.67	25.00
3.	I felt very confident using the system.	65.00	65.00	0.00
4.	I found the various functions in this system were well integrated.	81.67	80.00	-2.04
5.	I thought the system was easy to use.	61.67	76.67	24.32
6.	I thought there was too much inconsistency in this system.	81.67	85.00	4.08
7.	I found the system very cumbersome to use.	80.00	85.00	6.25
8.	I would imagine that most people would learn to use this system very quickly.	78.33	86.67	10.64
9.	I think that I would need the support of a technical person to be able to use this system.	70.00	83.33	19.05
10.	I needed to learn a lot of things before I could get going with this system.	80.00	91.67	14.58
	Global Score	**74.67**	**82.00**	**9.82**

It shows that generally subjects assign much better usability scores for the μRALP condition over the traditional condition. Further analysis on four specific sub-scales of the SUS shows the precise improvements:

1) Sub-scale 2 (25% better): The users of μRALP find the system simpler and more uniform.
2) Sub-scale 5 (24% better): The μRALP interface is easier to use than the traditional interface.
3) Sub-scale 9 (19% better): The users of the μRALP interface would require less support by an expert than the users of traditional system.
4) Sub-scale 10 (15% better): The users of μRALP would require to learn less processes than the users of traditional system.

The requirement of consistency and uniform integration in the system is taken as an important feedback. Towards this end, the latency in the video acquisition and display is an important factor in usability considerations. To evaluate the latency, time-stamped data was recorded over 10 seconds of system operation. A maximum latency of $66.6ms$ was registered for the visualization of the surgical video. This is more than 30% lower than the generally acceptable latency value of $100ms$.

V. Conclusions and Discussion

In this paper, a novel computer-assisted robotic system, the μRALP Surgical System, was presented. It was created to provide improved precision, safety, and better ergonomics for laser-based microsurgery procedures. These objectives were achieved with the implementation of the μRALP concept: a motorized laser micromanipulator, a stylus-based aiming controller, a configuration GUI, and a virtual microscope system based on an HD stereoscopic visualization device. The system maintains the proximity of the surgeon to the patient, allowing the same level of interaction between the surgeon and the surgical team as in traditional LP procedures. Delicate maneuvers can be accurately performed using a graphics stylus and a tablet interface, while high-resolution 3D visualization of the surgical area is realized through a virtual microscope device. Surgical capabilities are augmented through motion scaling and intuitive laser control. The system offers the possibility to further improve surgical procedures through active constraints and intraoperative planning.

A combined quantitative and qualitative evaluation also clearly demonstrated the superiority of the system. The results are summarized as follows:

1) The μRALP interface is superior and advantageous with regards to efficient, accurate, and safe operation.
2) The μRALP surgical system shows a much higher overall usability compared to the traditional interface. The different sub-scales indicate that it is an "easy to use" and "easy to learn" interface.
3) The results also imply that the μRALP interface takes much less time and effort to perform the surgical tasks.

In the extension of this research, further studies are planned in the optimization of the interface through an integrated framework for evaluation. The technological advances presented here are currently in the process of joint evaluation by surgeons and engineers using phantom tissues and ex-vivo pig larynxes as models. This will provide the groundwork for further evaluation with animal trials under real surgical conditions.

Acknowledgment

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