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Robot-assisted Microsurgical Forceps with Haptic Feedback for Transoral Laser Microsurgery

Nikhil Deshpande, Manish Chauhan, Claudio Pacchierotti, Domenico Prattichizzo,
Darwin G. Caldwell, and Leonardo S. Mattos
Department of Advanced Robotics, Istituto Italiano di Tecnologia (IIT), Via Morego 30, Genova, 16163, Italy
Email: {nikhil.deshpande, manish.chauhan, claudio.pacchierotti, domenico.prattichizzo,
darwin.caldwell, leonardo.mattos}@iit.it

***Abstract*—In laser-based laryngeal microsurgeries, hand-held, manual, microsurgical tools are used for intraoperative tissue manipulation and exposure. In this paper, a novel, motorized, multi-degrees-of-freedom (DoF), microsurgical forceps tool is presented, which is based on a master-slave teleoperation architecture. The slave device is a 7-DoF manipulator with: (i) 6-DoF positioning and orientation, (ii) 1 open/close gripper DoF; and (iii) an integrated force/torque sensor for tissue grip-force measurement. The master device is a 7-DoF haptic interface which teleoperates the slave device, and provides haptic feedback in its gripper interface. The combination of the device and the surgeon interface replaces the manual, hand-held device providing easy-to-use and ergonomic tissue control, simplifying the surgical tasks. This makes the system suitable to real surgical scenarios in the operating room (OR). The performance of the system was analysed through the evaluation of teleoperation control and characterization of gripping force. The new system offers an overall positioning error of less than 400 μm demonstrating its safety and accuracy. Improved system precision, usability, and ergonomics point to the potential suitability of the device for the OR and its ability to advance haptic-feedback-enhanced transoral laser microsurgeries.**

***Index Terms*—microsurgical forceps, robot-assisted, haptic interface, transoral laser microsurgeries**

I. Introduction

Robot-assisted surgical systems are increasingly becoming an accepted component of the state-of-the-art operating room (OR). This is due not only to the significant advantages they bring for surgery, such as increased precision, reduced instrument tremors, error-free and timely execution of repetitive tasks, etc., but also due to the improvements they bring for the surgeons themselves, with ease-of-use, comfort, and importantly, perception of the surgical site through high-resolution visualization and haptic feedback [1], [2]. It is observed therefore, that the quality and efficiency of the surgical outcome depends on both - the features of the surgical system and the skill and mastery of the surgeons using it [3]. This is especially true in the case of microsurgeries, such as transoral microsurgery, where the surgical areas within which the surgeons have to dissect and treat the abnormalities are quite small (in the order of *mm*). The finer the surgical procedure, the greater is the dependency on the dexterity and skill of the surgeon. These, in turn, depend on the controllability and precision of the robot-assisted surgical system [1], [3].

Transoral Laser Microsurgery (TLM) is a form of minimally invasive surgery which deals with the management of laryngeal and other head-and-neck malignancies, e.g., cysts, polyps, and tumours. The CO_2 surgical laser coupled with a surgical microscope is one of the main tools in TLM. A mechanical micromanipulator joystick is used by the surgeon to manually aim the laser beam for incisions at the surgical site from outside the mouth, as seen in Fig. 1. Microsurgical forceps are used for tissue manipulation, and a footswitch serves to activate the laser when desired. Considering the large operating distance (typically between 250 to 400 mm) and a small surgical area (typically 40 x 40 mm^2), the surgeons are required to be highly skilled to overcome challenges of: (i) poor operating ergonomics, (ii) difficult hand-eye-foot coordination, and (iii) manual, coordinated control of the tools for manipulation and incision of tissue. The situation is aggravated by the lack of any haptic perception, inadequate arm support, and uncomfortable wrist excursions. It is therefore highly difficult to make precise surgeries, maximising pathology removal, minimising damage to healthy tissue, and giving optimal surgical outcomes, e.g., voice quality.

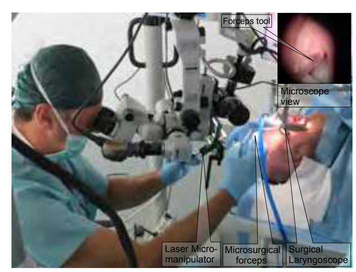

Fig. 1. Traditional TLM setup showing intraoperative use of microsurgical forceps

Earlier research by the authors has resulted in new and improved computer-assisted systems for TLM with a novel surgeon-machine interface (“Virtual Microscope” system [4]) providing: (i) a highly precise teleoperated laser aiming through a easy-to-use stylus tablet, (ii) improved ergonomics for high-resolution visualization and laser activation, and (iii) assistive intraoperative features for surgical enhancement. Taking motivation from these results, this paper extends the benefits of robot-assisted technologies to the critical aspect of tissue manipulation and presents the design and development of a novel, robot-assisted microsurgical forceps for precise and delicate tissue telemanipulation in

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TLM, with the surgeon using an ergonomic interface with haptic feedback for improved task and surgical perception. Haptic feedback is indeed widely considered to be valuable for teleoperated surgical procedures [5], [6]. It has been shown to enhance surgeon performance, through enhanced perception accuracy, decreased completion time, and decreased peak and mean applied forces, in a wide range of applications including needle positioning [7], telerobotic catheter insertion [8], suturing simulation [9], cardiothoracic procedures [2], palpation [10], cell injection [11], and more recently, improved laser guidance in TLM as well [12]. These benefits lend themselves readily towards facilitating and improving the complex suite of otolaryngological techniques of tool control involved in TLM.

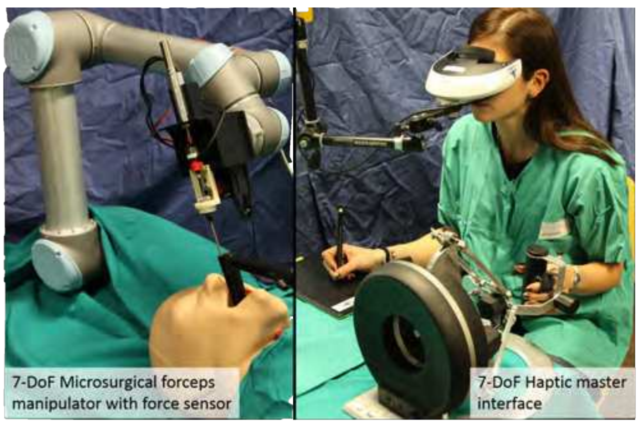


Fig. 2. Robot-assisted microsurgical forceps concept

The new robot-assisted microsurgical forceps design replaces the traditional, hand-held, manual tool with a teleoperation system consisting of: (i) a 7 degree-of-freedom (DoF) microsurgical forceps manipulator; (ii) a 7-DoF teleoperation haptic master interface, the *Force Dimension Omega.7* [13]; and (iii) an integrated force/torque sensor for haptic feedback, the ATI Nano17 [14]. The features and benefits include: (i) improved precision, safety, and controllability; (ii) enhanced surgical site perception with haptic feedback; and (iii) intuitive and ergonomic operation of the microsurgical forceps with a common surgeon interface with gesture scaling. The developments presented here, integrated with the "Virtual Microscope" system from [4] shall lead to a holistic, robot-assisted surgical system for TLM. The concept is shown in Fig. 2.

II. RELATED WORK

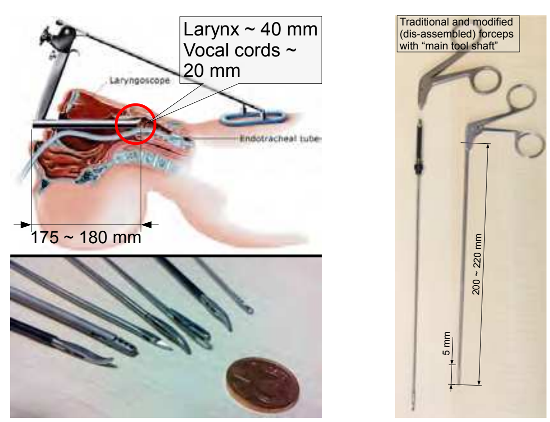
Robot-assisted surgical instruments for transoral surgery have been a subject of extensive research. Simaan et al. [15] introduced snake-like manipulators with high tip dexterity for tissue manipulation and suturing. Similarly, He et al. [16] presented a cooperatively controlled bimanual teleoperation robot having 3-DoF wrists with surgical tools attached. Wang et al. [17] presented a new robot-assisted master-slave laryngeal surgery system consisting of two symmetrical 9-DoF manipulators, with quick-change interfaces for surgical tools. Rivera-Serrano et al. [18] presented a highly articulated robot in a follow-the-leader mechanism using a master controller. The robot had two working ports (channels) through which flexible instruments (ϕ 3 mm) could be inserted for tissue manipulation.

Although these research efforts have significantly advanced the state-of-the-art in surgical tools, they are focused on cold-steel instrument-based surgery and not transoral laser microsurgery. The typical instrument shaft diameter in cold-steel surgeries is 3 mm and higher, while in TLM, the tools are typically around 2 mm in diameter. In the domain of TLM, Solares and Strome [19] and Desai et al. [20] explored the utility of the *da Vinci Surgical System* [21]. The important limitations here were the attendant changes needed in the current TLM surgical methodology, and again, the sizes of the *da Vinci* tool shafts. Alternatively, Maier et al. [22] presented an effective solution with a lightweight manipulator to which standard surgical tools can be attached directly without any modification. This meant that typical tool-shafts of ϕ 2 mm could be directly used while allowing a common interface for the surgeon irrespective of the tool.

The developments in this paper are guided by the approach of having a common interface for the surgeon. The desire is to enable surgeons to use standard TLM microsurgical instruments, but with added features and haptic feedback to improve their usability, accuracy, and safety.

III. HARDWARE DESIGN

In the state-of-the-art TLM procedure, a laryngoscope is used to expose the surgical site allowing direct line-of-sight for the surgical microscope, as seen in Fig. 1. The laryngoscope has a length of 180 mm and a cross-section of 17 mm (Fig. 3a) [17]. Microsurgical tools, e.g., forceps, are manually operated through the laryngoscope and help the surgeons in: (i) exposure of surgical site pathology; (ii) tissue manipulation; (iii) tissue palpation; and (iv) orienting the tissue to be perpendicular to the laser path, in traction (stretched), for precise cuts with minimal thermal damage (Fig. 1).



(a) Anatomical dimensions and tool variety in TLM

(b) Microsurgical forceps dimensions

Fig. 3. Microsurgical anatomy and tools in TLM

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State-of-the-art microsurgical forceps are long and rigid, with a scissor-like grasping handle at the proximal end and an average shaft length of about 200-220 mm. They have an average tool-shaft cross-section of about 2 - 3 mm and are usually pre-curved to the left or right for accessing the two sides of the larynx, as seen in Fig. 3. The manual tools are single purpose, i.e., available with only 1 DoF (open/close). The TLM surgical area, the larynx, is a highly restricted space, varying from about 45 mm (diagonal length, males) to about 25 mm (females) [23]. Furthermore, in laryngeal vocal cord surgery, the sizes reduce to about 11 - 21 mm [24]. The procedure therefore, demands a great level of accuracy and dexterity on the part of the surgeon for coordinated bimanual control to guarantee total pathology removal. Hand tremors and extreme wrist excursions are induced from manually operating the long tools in a constrained space for long surgical hours, negatively impacting surgical outcomes and the resulting voice quality of the patient. The attendant surgeon discomfort and fatigue makes the surgery vulnerable to safety issues as well.

The research in this paper addresses these issues by redesigning the surgeon interface for tissue manipulation. The limitations can be overcome by providing the surgeons with an ergonomic, easy-to-use interface which operates a multiple DoF forceps tool that improves accuracy, reduces the dependence on operator dexterity, facilitates tissue manipulability and surgical exposure, and provides tissue force feedback for better intra-operative perception. The redesign utilizes the traditional forceps as the basis tools; the tool shaft and gripper of the traditional forceps are used and proximal mechanisms are introduced to incorporate added DoFs, sensors, and actuators.

A. Redesign of existing microsurgical forceps

A modular architecture was adopted in the redesign of the forceps tool giving a common surgeon interface while allowing interchangeability of the different tool-tips that are commonly used in TLM (Fig. 3a). Fabricating the components using ABS-plastic through additive manufacturing allowed maintaining a low profile in costs, sizes, and weights. The motivation of the design was to build a standalone motorized microsurgical forceps, with an additional rotational DoF which would allow: (i) gripping-n-turning of tissue for better surgical exposure; and (ii) improving the surgical access to different parts of the larynx. Existing TLM microsurgical forceps were dis-assembled and three individual modules were designed as part of the novel forceps: (i) Main tool shaft; (ii) Mechanism housing; and (iii) Actuator housing.

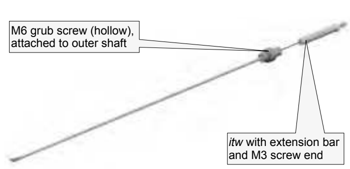

Fig. 4. Main tool shaft - adaptations

1) Main Tool Shaft (mts): This component consists of an outer shaft (ϕ 2.5 mm) and an inner translating wire (*itw*, ϕ 1 mm) for the open/close DoF (Fig. 4). The distal end of the *mts* consists of a dual-jaw gripper with ϕ 2 mm and length of 5 mm. Two adaptations are introduced at the proximal end of the *mts*: (i) a hollow M6 grub screw is attached to the outer shaft; and (ii) the *itw* is outfitted with an extension bar (~ 31 mm) and an M3 screw at the end. Both these adaptations act as docking interfaces for the "Mechanism housing".

Fig. 5. Mechanism housing

2) Mechanism housing (mh): This component houses the mechanisms for the original open/close DoF and the newly introduced rotational DoF (Fig. 5). The added rotational DoF allows the surgeons to grip-n-turn the tissue for better exposure and manipulation. Along with the links and connectors to the sensors/actuators, the housing consists of:

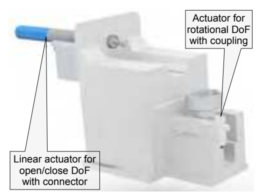

Fig. 6. Actuator housing

1) Rotational DoF: An anti-backlash, hollow, miter gear assembly (Nordex LHS E2-30) provides the rotation of the main tool shaft. The M6 grub screw of the *mts* fits into an M6 brass-insert fixed to the *axial* miter gear. The *itw* is made to the pass through the axial miter gear. A connector on the *normal* miter gear couples it to the actuator.
2) Open/Close DoF: The *itw* is attached to a "sliding cylinder assembly" (*sca*) through an M3 brass-insert. The sliding cylinder includes an internal bearing to allow free motion of the *itw* with the rotational DoF. The other end of the cylinder has a connector for coupling to the actuator.

3) Actuator housing (ah): This component houses the two actuators used for the two DoFs (Fig. 6). A linear actuator (CAL12 series) is used for the open/close DoF and is coupled with the *sca*. A rotary motor (Maxon GM20) provides the rotational DoF through its coupling with the miter gear assembly in *mh*.

Fig. 7. Assembly of the 2-DoF motorized microsurgical forceps

These adaptations result in the 2-DoF motorized microsurgical forceps device shown in Fig. 7.

B. 7-DoF manipulator: Integration of forceps with a robotic manipulator and force/torque sensor

The motorized microsurgical forceps assembly is attached to the 6-DoF robotic manipulator, the Universal Robots UR5 [25], and integrated with the 6-axis force/torque sensor, the

ATI Nano17 [14], to form the 7-DoF microsurgical forceps manipulator, as shown in Fig. 8a.

(a) Universal Robots - UR5 mounted with the 2-DoF motorized forceps

(b) The *Omega.7* device (top) and the ATI Nano17 (bottom)

Fig. 8. Hardware devices in the system

The 2-DoF microsurgical forceps are attached to the end-effector wrist of the UR5 at a 90° angle. Since the new forceps tool already has a rotational DoF, the final wrist DoF of the UR5 is unused. The Denavit-Hartenberg parameters for the device are suitably updated to operate as a 7-DoF manipulator. For haptic feedback, the placement of the ATI Nano17 Force/Torque sensor needs to be optimal in allowing the sensing of the tissue gripping force. The sensor is located as part of the *sca* of the open/close DoF in *mh*, with the z-axis of the sensor axially coincident with the *itw*, as seen in Fig. 5.

Finally, the master haptic interface, the 7-DoF *Force Dimension Omega.7,* equipped with an active gripper, is used to teleoperate this 7-DoF robotic forceps manipulator.

IV. Control Design

The 2-DoF motorized microsurgical forceps are controlled through a custom designed motor control board, based on the TI–LM3S microcontroller. Custom PID control code allows both position and velocity-based control of the actuators. Linux-based software was written using the open-source Robot Operating System (ROS) platform for controlling the 7-DoF manipulator.

In this work, the *Omega.7* interface was used as an impedance haptic device. The measured position of the haptic end-effector controlled by the operator sets the reference target position for the microsurgical forceps gripper. At the same time, through the same haptic end-effector, the operator is provided with the force feedback from the slave environment. The device allows gesture scaling and tremor suppression between the master and slave environments. The haptic feedback on the *Omega.7* gripper can also be tuned based on surgical preferences. The haptic control loop runs at 2 kHz.

A. Motion Control

The velocities of the robotic manipulator joints $\dot{q} \in \mathbb{R}^6$ can be expressed as:

$$\dot{\mathbf{q}}_\mathbf{r} = \mathbf{J}^{-1}\dot{\mathbf{q}}_\mathbf{h}\zeta \tag{1}$$

where $\mathbf{J}^{-1}$ is the inverse of the manipulator Jacobian matrix $\mathbf{J} \in \mathbb{R}^{6x6}$ and $\dot{\mathbf{q}}_\mathbf{h} \in \mathbb{R}^6$ are the velocities of the *Omega.7*'s end-effector. The $\dot{\mathbf{q}}_\mathbf{h}$ velocities of the haptic end-effector are scaled through a low-pass filter in (2), with a tunable factor β to control the level of high-frequency tremor suppression.

$$\dot{\mathbf{q}}_\mathbf{h}^{k} = (1-\beta)\cdot\dot{\mathbf{q}}_\mathbf{h}^{k-1} + \beta\cdot\dot{\mathbf{q}}_\mathbf{h}^{encoder} \tag{2}$$

The gesture scaling factor ζ is tunable to allow coarse and fine gestures in different stages of operation. For instance, a value of 0.2 in all directions implies that moving the haptic end-effector by 10 cm would move the forceps gripper's reference position by 2 cm. The speed of motion is also controlled simultaneously.

As mentioned earlier, the system is managed by a GNU/Linux machine using ROS Jade. To preserve the stability of the teleoperation system, a time-domain passivity controller was used [26]. The *Omega.7*'s gripper DoF is mapped directly to the open/close DoF of the microsurgical forceps through simple position control.

V. Evaluation and Discussion

The performance of the motion control and the variance in the haptic gripping force were evaluated through characterization trials.

A. Motion control evaluation

The robot-assisted microsurgical forceps tool is intended for telemanipulation of tissue. This implies that the surgeon shall be controlling the microsurgical forceps while simultaneously visualizing the actions through visual feedback of the surgical site, making it a human-in-the-loop feedback system. The gestures of the surgeon on the haptic master interface are directly mapped to the slave environment, allowing for any positioning and orientation corrections in real time. Therefore, the evaluation is intended for defining how well the master interface motions are replicated by the slave device.

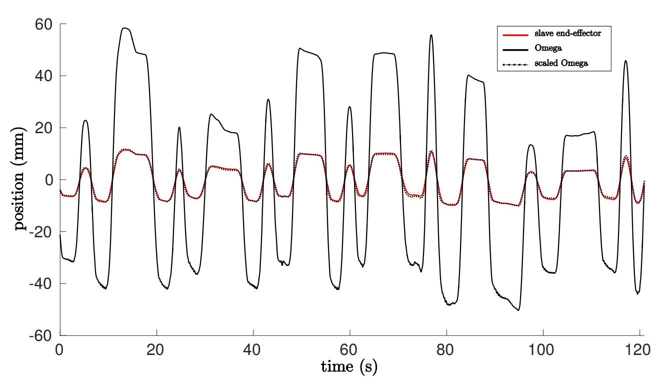

Fig. 9. Motion control evaluation

The evaluation characterized the relationship expressed in (1). The integrated system was tested by moving the haptic

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master interface in free-space over a period of 120 seconds, and recording the position of the slave device. Figure 9 shows a representative graph for a evaluation for a single axis of the end-effector. A gesture scaling factor of $\zeta = 0.2$ was used for the evaluation. As can be seen, the slave device is able to track the gestures of the master interface very well. The overall error, over the 120 seconds, in the 3-axis positioning of the slave device end-effector was found to be **0.3901 mm** (RMSE) with a standard deviation of **0.3829 mm**. The position mapping error is therefore less than 400 μm.

B. Haptic feedback characterization

The levels of tissue gripping force vary with the amount of gripping on the tissue, i.e., on the amount that the jaws of the gripper are closed. An independent evaluation was made to quantify the haptic force to be fed back to the haptic master interface. Here, a high-precision X-Y table (Siskiyou 1620-XYZR [27]) was integrated with the mechanism housing of the modified microsurgical forceps, with the ATI Nano17 located in place. This allowed precise control of the closing angle of the forceps gripper jaws (with a resolution of ~ $1°$) and the sensor output signal was recorded for different angles of the jaws. Ex-vivo chicken tissue samples (min. 40 x 40 mm^2 area and 5 mm thickness) were used for the trials. For every angular position of the gripper jaw the sensor values were averaged over 5 trials with 5 different tissue samples. As seen from Fig. 11, the gripping force increases non-linearly from the fully-open position of the gripper jaws (~ $80°$, the tissue not touching the jaws) to the fully-closed position (indicated as $0°$). A maximum gripping force of about 16 N is noted from the trials. This information is helpful in sizing the actuator for the open/close DoF of the tool. The force feedback is mapped to the input of the active gripper DoF of the *Omega.7*, and scaled according to surgical preferences.

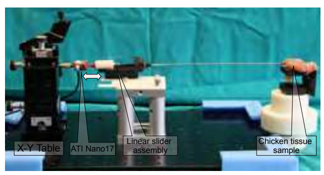

Fig. 10. Tissue gripping force characterization setup

VI. Conclusions and Future Work

This paper presented a novel design of a modular, integrated, multi-DoF, motorized microsurgical forceps tool for intraoperative use in transoral laser microsurgeries. The new design replaces the traditional, hand-held, manual tool with a teleoperation system consisting of: (i) a 7 DoF microsurgical forceps manipulator; (ii) a 7-DoF teleoperation haptic master interface; and (iii) an integrated force/torque sensor for haptic feedback of the tissue gripping force. The system provides: (i) improved precision, safety, and controllability with a positioning error less than 400 μm; (ii) enhanced surgical site perception with haptic feedback which can be tuned suitably based on surgical preferences; and (iii) intuitive and ergonomic operation of the microsurgical forceps with a common surgeon interface providing gesture scaling and overcoming the problems of hand tremors and wrist excursions. The developments presented here, integrated with the "Virtual Microscope" system from [4] shall lead to a holistic, robot-assisted surgical system for TLM, enhancing the capacity for safer minimally invasive microsurgeries, requiring delicate and precise actions.

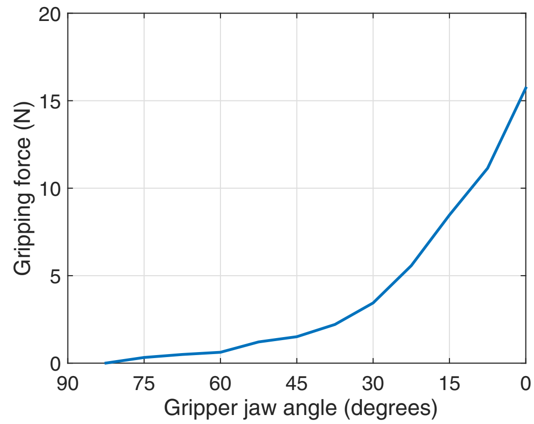

Fig. 11. Characterization of tissue gripping force using the ATI Nano17 and X-Y table

In the extension of this research, the evaluation of the new tool with user trials shall be investigated. These shall provide a comparative performance analysis against the traditional forceps tool. As noted earlier, the operating workspace in TLM is highly restricted. Active constraints shall be implemented in the control of the forceps tool to improve the safety of operation. The ATI sensor provides 6-DoF force/torque data, and the use of this information shall be investigated for multi-dimensional haptic control of the new forceps tool. The ultimate goal is to evaluate the robustness and safety of the mechanism in real operating conditions. Clinical trials with expert surgeons using ex-vivo, cadaver, and in-vivo trials would provide valuable feedback on improvements required in the usability and safety of the system as well as the proof required to make the new tool applicable, usable, and advantageous in the real surgical scenario.

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