2024 IEEE International Conference on Robotics and Automation (ICRA 2024)
May 13-17, 2024. Yokohama, Japan

# Design and evaluation of a modular robotic system for microsurgery

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***Abstract*— The manipulation of instruments under a microscope suffers from physiological tremor and human errors, which are inevitable in long microsurgery interventions. Robotic systems developed in recent years for microsurgery are expensive and not flexible, as they cannot use standard instruments, and need the surgeon to modify their operative skills and strategies. In this paper, we introduce a modular robotic system for microsurgery enabling the surgeon to operate using conventional instruments. Our system was implemented using a commercial Kinova robot and a dedicated modular end-effector that uses standard microsurgery instruments. An initial teleoperation validation was carried out by eleven participants, who could successfully control the microsurgery tools to perform basic surgical movements. Furthermore, participants performed a simple anastomosis task with the robot and compared it to manual control. The results showed that robotic control is superior to manual control in simple surgical tasks and the converse in complex tasks. Participants preferred the proposed robotic system due to its user-friendliness and effort reduction.**

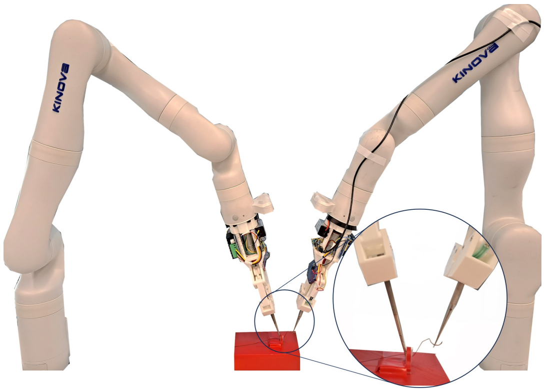

Fig. 1. The overall robotic-assisted system for microsurgery with modular end-effector holding the general microsurgical instruments.

## I. INTRODUCTION

Microsurgery, or surgery performed under the microscope using dedicated instruments with fine tips [1], is critical to carry out complex interventions including reconstruction of damaged skin, nerves, blood vessels, muscles, and tissues. Microsurgery usually involves long operating hours and requires high concentration and precise operation [2]. Human fatigue is inevitable and may lead to increasing tremor, which could highly affect the outcome of the surgery [3].

Multiple robotic systems have been developed to offer ergonomic and accurate control for surgeons [4], [5]. The Da Vinci system (Intuitive Surgical Inc., USA) [6] enables surgeons to remotely manipulate surgical instruments held by the robot on the patient's side and conduct minimally invasive procedures. The system is widely used for many surgical disciplines, including otolaryngological surgery, neurosurgery, gynecological surgery, and some microsurgery. Some dedicated robots have been developed specifically for microsurgery focusing on tremor filtering and scale-down motions [7]. The MUSA system (MicroSure, Eindhoven, The Netherlands) is a robotic platform for microsurgery that has been validated in preclinical tests [8] and recently first tested in humans [9]. Symani robotic system (Medical Microinstruments, MMI, Calci, Italy) has been commercialized to perform microsurgery including specialized microinstruments that have been tested to conduct anastomosis in lymphatic reconstruction [10].

These existing robotic systems for microsurgery can improve operation accuracy and ergonomics. However, they require specialized systems and instruments which make them bulky and expensive [11]. Furthermore, the surgeon will require additional training for using the robotic system and may not be able to transfer the skills from/to conventional procedures using standard instruments or from a different robotic system [12], [13]. In this paper, we present the concept of a modular robot for reconstructive microsurgery that builds upon conventional microsurgery. The system consists of a kinova robot and a developed robotic end-effector, and can integrate standard microsurgical instruments, e.g., needle holders, forceps, scissors. The operator can teleoperate with the microsurgical tools through a hand controller with haptic feedback. The proposed system is evaluated in an experiment with eleven participants, where the proposed system is compared with conventional manual control in a mock anastomosis task.

## II. SYSTEM DEVELOPMENT

The microsurgery robotic system shown in Fig. 1 is composed of a 7-DoF robot (Kinova Inc., Canada) with a dedicated robotic end-effector that can adapt to different microsurgery instruments.

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This work was supported by the EC H2020 grants NIMA (FETOPEN 899626) and CONBOTS (ICT 871803).

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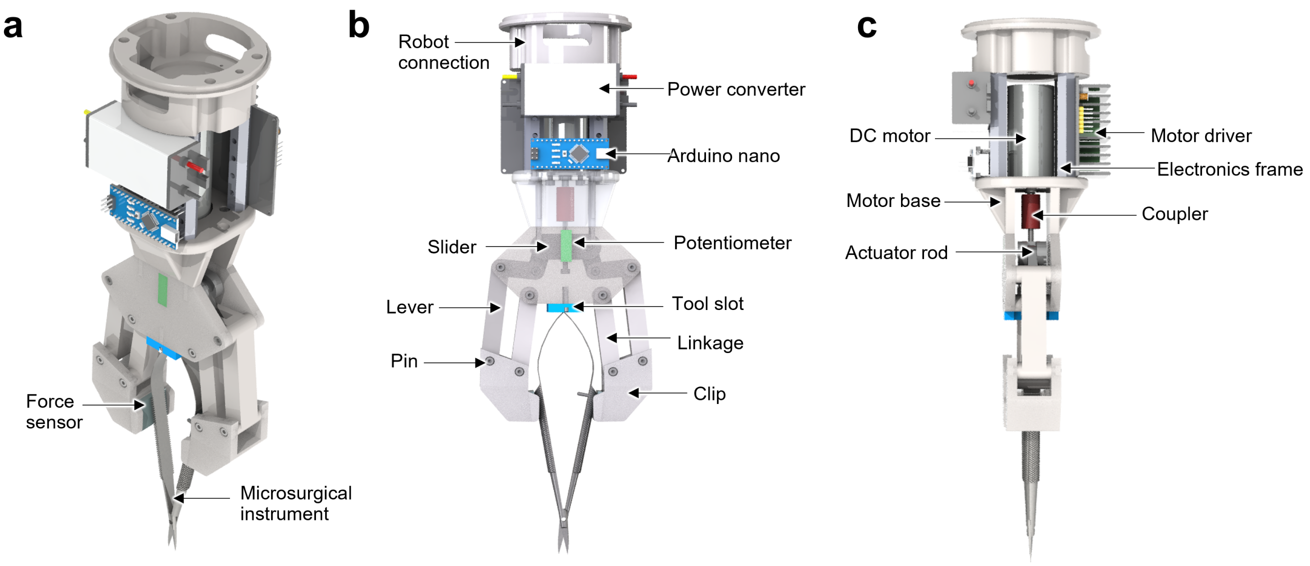

Fig. 2. Design overview. 3D drawing of the robotic end-effector for microsurgery tool in (a) perspective view, (b) front view, and (c) side view.

## A. Modular end-effector

The robotic end-effector is illustrated in Fig. 2. It includes two main parts: the parallel gripper mechanism connecting with standard instruments, and its motion-driving system. The motion-driving system has a brush DC motor (GA25-370, Hilitand) connected to a motor driver module with the heat sink (DBH-1A, Hilitand, China). The motor is connected to the activation rod through a coupler and drives the rod to move up and down. This movement will open and close the parallel linkage mechanism to control the instruments like human fingers. The force sensor (FSR402, Interlink Electronics) is located at the right side of the clip tips which records the gripping force of the microsurgical instruments. A slide potentiometer (B102, Sourcing map) is used to detect the position of the slider.

The instruments used in this study are from the general Castroviejo microsurgery tool set shown in Fig. 3 including needle holder, forceps, and scissors. The needle holder is used to hold sutures or very small-sized stitches. The microsurgery forceps can be used to manipulate and hold tissue and suture materials. The microsurgery scissors are used for cutting tissue or sutures.

The replacement of the instruments is quick and easy so that a naive operator can change the instruments within 15 seconds (see video `https://youtu.be/QHXr8IfnWCw`). The operator can simply press one button of the Xbox remote controller to open the clamp jaw, remove the old tool, put the new tool inside the slot, and close the clamp jaw by pressing another button. The initial positions of the different instruments can be automatically set up based on the detected gripping force with a threshold of 1.47 N which is based on the human finger force to hold the instruments.

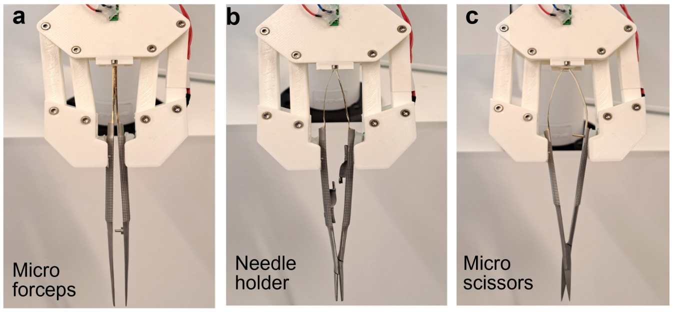

Fig. 3. Robotic end-effector with microsurgical instruments of (a) micro forceps, (b) needle holder, and (c) micro scissors.

## B. Modeling and kinematics

*1) Robotic instrument:* The end-effector mechanism is shown in Fig. 4a. The motor driving rod moves link AA' vertically to drive the following link AB and A'B'. Since the links are symmetrically located along the central line MM', we will inspect one side of the mechanism. The black lines represent the configuration when the end-effector is fully closed, while the grey lines represent its fully open state. If we place a coordinate system in point O, point A can be represented as $x_A, y_A$, which is decided by the initial configuration and the rod sliding distance. The joint B's coordinate can then be determined as

$$x_B = L_3\cos(\alpha),\quad y_B = L_3\sin(\alpha)$$
$$\alpha = \arctan\left(\frac{y_A}{x_A}\right) - \arccos\left(\frac{L_3^2 + x_A^2 + y_A^2 - L_2^2}{2L_3\sqrt{x_A^2+y_A^2}}\right) \tag{1}$$

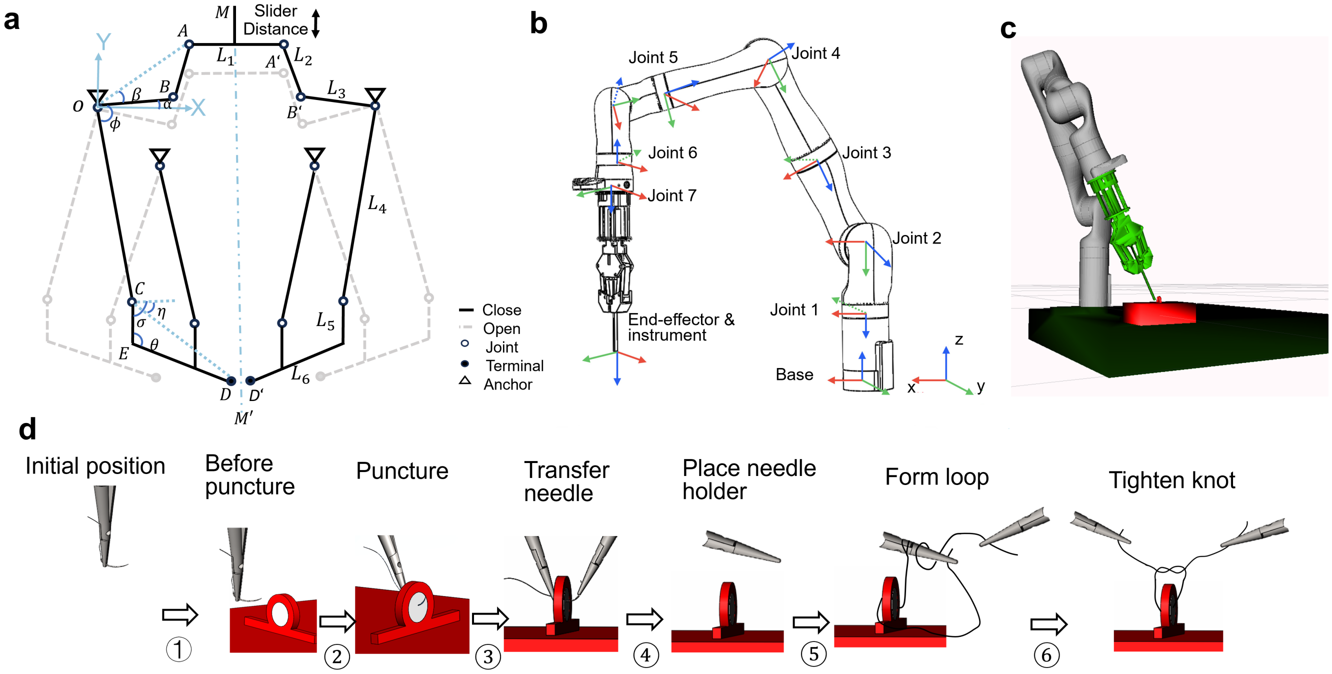

Fig. 4. Robotic system kinematics and simulator. (a) robotic end-effector linkage mechanism, (b) the Robot's joints and axes, including the end-effector and the held instrument, (c) the simulated system, with the interaction objects, and (d) the demonstration of the operation procedure of the suture task.

Then the clip jaw position D can be calculated as

$$\begin{aligned} x_D &= L_4 \cos(\phi - \alpha) + L_{CD} \cos \eta, \\ y_D &= L_4 \sin(\phi - \alpha) + L_{CD} \sin \eta, \\ L_{CD} &= \sqrt{L_5^2 + L_6^2 - 2 L_5 L_6 \cos \theta}, \\ \eta &= \sigma - \arccos\left(\frac{L_5^2 + L_{CD}^2 - L_6^2}{2 L_5 L_{CD}}\right) \end{aligned} \tag{2}$$

Then, the two jaw distance $d$ in horizontal direction can be derived as, $d = L_1 + 2(x_A - x_D)$. The maximum open distance is about 30mm. The lengths of the links are known and set in the mechanism as $L_1 = 25mm$, $L_2 = 15mm$, $L_3 = 20mm$, $L_4 = 55mm$, $L_5 = 14.4mm$ and $L_6 = 29mm$. The angles $\phi$ and $\sigma$ are also set as constant values which are 90° and 104°.

*2) Robotic system:* To control the robot, commands are sent in either Cartesian space or joint space coordinates (Fig. 4b). The forward kinematics (FK) from joint space to Cartesian space can be represented as

$$FK(q) = {}^{Base}T_{instrument} = {}^{Base}T_1\,{}^{1}T_2 ... {}^{7}T_{instrument}$$

where ${}^{m}T_n$ are kinematics transformation matrix from frame $m$ to frame $n$. In the case that the conveyed command includes the input of the instrument's Cartesian pose, inverse kinematics (IK) can be applied to obtain the respective joint values through the Pieper technique [14].

In addition, we have built a simulator for the microsurgery robotic assistant using the Robot Operating System (ROS) to plan and certify the motion trajectories before using the real robot. The robot's configuration, proposed end-effector, and the interaction environment are interpreted into ROS nodes and displayed using the 3D visualization tool RViz (Fig. 4c).

### *C. Control and interaction*

*1) Robotic instrument:* There are two control modes to control the opening and closing angle of the microsurgery instruments: binary and continuous modes. The control mode is selected based on the function of the instrument. In the binary control mode, the operator just needs to press the close control button once, the tool will close to an angle and hold there. The needle holder uses the binary control to make sure the needle can be held tightly and does not affect the hand operation of the needle. In contrast, the forceps is used to manipulate tissue or suture and may need to adjust the gripping force frequently. Then it is controlled in a continuous mode in which the operator can control the instrument's opening & closing by pressing or releasing a bumper button of the remote controller. The position of the finger (0-9 mm) is scaled and mapped to the opening distance (0-5 mm) of the tip of the micro forceps.

To assist the force control of the operator using forceps, vibration haptic feedback is provided to the user. The amplitude of the vibrations can remind the user of the interaction force levels on the remote side. In the current setup, we have started to set two levels of vibrations to the user's finger with 10% of the maximum intensity set by Xbox controller for 4-6 N gripping force, and 90% of total intensity for the force larger than 6 N.

*2) Human-robot collaboration:* The system enables the robot to perform semi-autonomous operations under human supervision and collaborate with the operator to perform bimanual tasks. The human operator supervises and gives high-level control commands to the robot that performs the low-level actions. We initially break down the task into a series of subtasks, each aligned with the timing of decision-making or cooperating by the operator. At the onset of each subtask, the operator has the opportunity to adjust the instrument and confirm their intent to proceed with the task. Upon receiving the user's approval (usually by pressing a button on the controller), the robot then executes predefined trajectories. These trajectories are calculated based on observations of microsurgeons' movements [1], [15], [16].

We use a simplified puncture and knot-tying task of interrupted suturing [1] as an illustration. As shown in Fig. 4d, the silicon simulates the operation tissue, and we assume its physical properties and spatial position are known. The initial three subtasks involve puncturing, followed by three subsequent subtasks dedicated to knot-tying. The robot initially moves the needle from its starting position to the front of the tissue upon receiving approval from the operator. The human operator could determine whether they need to adjust the needle position manually using the admittance control of the robot or allow the robot to perform the next step. In subtasks 2 & 3, the robot punctures the tissue following a curvature path and releases the needle as the operator picks the needle on another side. Afterward, during the subsequent knot-tying phase, the robot repositions itself upon receiving the operator's command in subtask 4. The operator forms the loop using one hand (subtask 5) and then instructs the robot to pull in the opposite direction while coordinating with their natural hand to tighten the knot (subtask 6).

## III. EXPERIMENT

The experiments were approved by the Research Ethics Committee of Imperial College London (21IC7042). We recruited 11 participants (3 females and 8 males) between 21 to 37 years old for this study. Each participant was informed about the experiment's purpose and protocol and signed a consent form before starting. All but one participant had no prior experience with robotic teleoperation devices, and nine of the eleven participants did not have a medical background. The experiment is separated into two phases: evaluation of the robotic end-effector with microsurgery instruments and evaluation of the whole robotic system in a surgical task.

### A. Evaluation of robotic end-effector

There are two tasks in the first phase of evaluating the microsurgical robotic end-effector: pick & place for the needle holder (Task 1) and force control for the micro forceps (Task 2). The experimenter gives an explanation of how to use the system and the participant is given 5 minutes to get familiar with the control before the tasks. Between the two tasks, the participant is asked to change the instruments by themselves which includes unloading the needle holder and mounting the forceps, and the changing time is recorded.

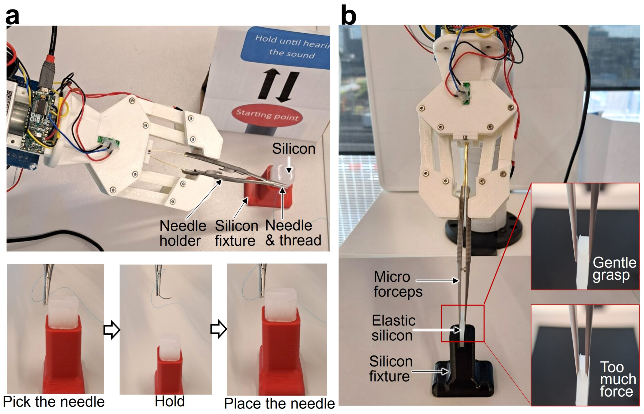

Fig. 5. Experiment setup for testing the robotic end-effector for micro-surgery. (a) Task 1, pick and place task using the needle holder. (b) Task 2, force control task to test the micro forceps.

*1) Task 1: Pick the needle using the needle holder:* As shown in Fig. 5a, Task 1 includes three actions: (1) pick up the needle using the needle holder, (2) hold the needle for 5 seconds without dropping it, and (3) place the needle back in its initial position. The needle holder operates in a binary mode, allowing for either an open or closed position. The participants were asked to complete the task five times using either manual (with the dominant hand) or robotic control, with the order randomized.

*2) Task 2: Force control using micro forceps:* The second task is testing the force control of micro forceps using the proposed system with and without haptic feedback. The micro forceps is remotely controlled using the hand controller in a continuous control mode. As shown in Fig. 5b, the participant is required to hold the instrument with gentle force (around 4 N, no more than 6 N at the jaw gripping point) to pick up the silicon, lift it up, and then put it back in its original position. The elastic silicon with 3 mm thickness deforms with the increase of the gripping force, where the deformation could help the operator to check the force. Half of the trials are with and the others are without haptic feedback. The participants start randomly with or without haptic feedback.

### B. Evaluation of robotic system

In the second phase of the experiment, the participants are required to perform a simplified anastomosis task (Fig. 4d). Before the task, each participant was given 5 minutes to familiarize the motion control of the robotic system using the Xbox controller through pilot tasks of reaching the target positions and following the rectangular trajectory. Then they were instructed to perform puncture and knot typing operations in the experiment and practice until they felt ready for the test. The needle and thread used in the test are a 19mm reverse cutting needle and a 75mm silk braided suture.

The experiment setup is shown in Fig. 6. The participants randomly started with manual control without the robot or human-robot cooperation control with the robot. In the

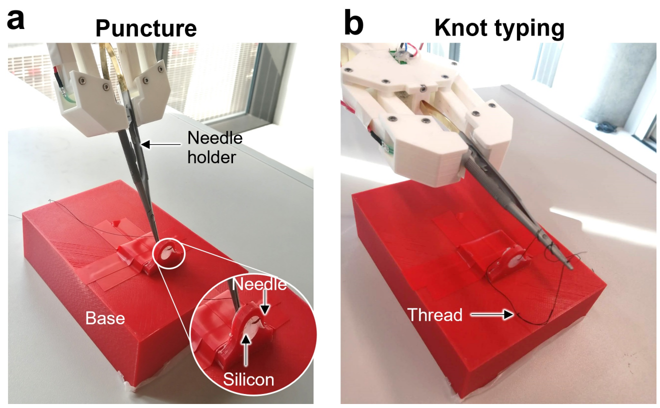

Fig. 6. Experiment setup for the suture task. (a) Puncture the silicon and (b) knot typing.

manual control, the participants performed the task using both hands, with the left hand controlling the needle holder to puncture the tissue and the other hand manipulating micro forceps to grasp the needle, and then performing knot tying around the silicon. In the robotic control mode, the robot holds the needle holder and cooperates with the human operator's right hand (see section II-C.2). Three trials were performed for each control mode. The operation time was recorded, and the participants were asked to rank the preference and difficulty and fill in their perceived physical effort (10 Likert scale) using two control modes. In addition, at the end of the experiment, the participants were asked to evaluate the usability of the proposed robotic system through the System Usability Scale (SUS) [17], [18].

## IV. RESULTS

### A. *Testing the robotic end-effector*

The completion time of task 1 was normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.4$ for both control modes). As shown in Fig. 7a, the robotic control mode spent $11.18 \pm 0.72$ seconds to complete the task, which is more efficient than manual control of $12.18 \pm 0.84$ seconds ($t(10) = -4.56$, $p = 0.001$). Furthermore, the participants could quickly change the instruments from the needle holder to the micro forceps in $12.20 \pm 3.54$ seconds.

For task 2, most of the participants were able to maintain the average remote gripping force between 4-6 N in both control modes of with and without force feedback (Fig. 7b). No obvious difference between the two modes is observed on the average force ($t(10) = -0.92$, $p = 0.38$). However, if checking the result of each participant among five trials, it could be found that the effect of the haptic feedback is diverse between subjects (Fig. 7c). For about half of the participants, the haptic feedback provided positive effects to allow more consistent holding forces with smaller deviations between trials and/or the force was maintained to relatively small values toward the lower end of 4N. For other participants, the haptic feedback does not affect the performance or is even disturbing, i.e., subjects 5 and 11.

### B. *Robot system evaluation*

*1) Performance on suture task:* As shown in Fig. 8a, the manual control is faster than robotic control. A Wilcoxon signed-rank test determined that there was a statistically significant median increase in completion time when subjects using the robotic system (71.79 s) compared to the manual operation (33.13 s), $z = -3.02$, $p = 0.003$.

However, the robotic control is preferred than manual control on subjective rankings. As shown in Fig. 8b, the participants felt the robotic control obviously saved their physical effort more than the manual control ($z = 2.34$, $p = 0.02$). In addition, the subjective response of preference and difficulty shows a similar tendency. 72.7% of participants felt manual control without the robot is more difficult to perform than robotic control. 63.6% of participants prefer robotic control instead of manual control.

*2) Evaluation of usability of the robotic system:* The participants have provided positive feedback on the usability of the proposed robotic system. The SUS questionnaire result on ten questions is shown in Fig. 9a. Most participants agreed that they would like to use the system frequently and felt the system is easy to use, various functions are well integrated and they are confident to use the system. The overall SUS score is calculated and plotted in Fig. 9b. The average SUS score of all participants is $72.5 \pm 14.0$. Seven out of eleven participants believed the robotic system was "Good" with SUS scores of more than 75, in which two of them provided "Excellent" feedback. Ten out of eleven participants felt that the robotic system was acceptable or marginally acceptable.

## V. DISCUSSION

This paper presented the design and evaluation of a modular robotic system for microsurgery. The system can be easily integrated with different standard microsurgical instruments. The experimental study evaluated the robotic end-effector and the whole system and showed the feasibility of the robotic system to perform simple surgical operations and enable human-robot collaboration in bimanual tasks.

The experiments conducted highlighted the efficiency of the end-effector in terms of instrument interchangeability, with participants taking an average of only 12 seconds. The simple pick & place task indicated a reduction in completion time when using the robotic end-effector compared to manual execution. When it comes to complicated operations like suturing, manual control demonstrates superior operational efficiency compared to robotic control, but users prefer working with the robot, especially among operator with limited medical experience. The interactive strategy allows the robot to perform part of the operation under the human operator's commands, effectively sharing the workload and reducing the operator's physical effort. The responses to the SUS questionnaire also showed the participants generally felt the proposed system acceptable and user-friendly.

Limitations of the current system include the limited repeatability and robustness of the system, that should be addressed in future work. We further plan to investigate

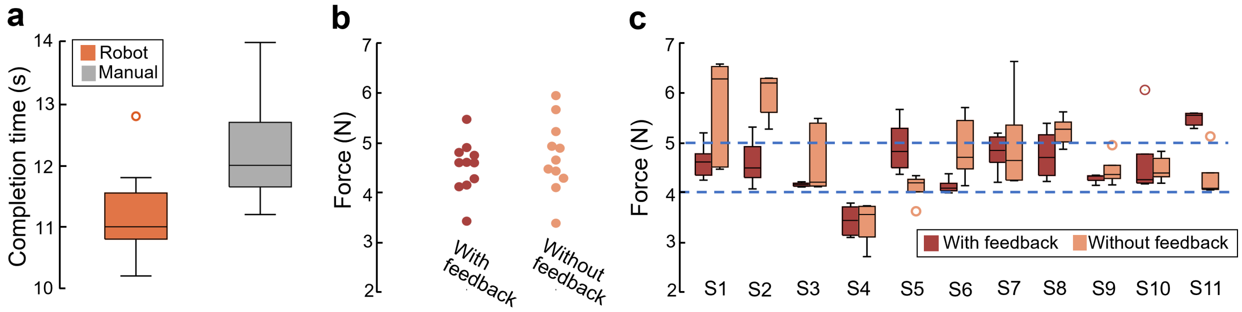

Fig. 7. Results of testing the end-effector. (a) completion time of the pick & place task using the needle holder. (b) Force of gripping the tool in the force control task with and without vibration force feedback. (c) Boxplot of the gripping force (over five trials) used by the 11 subjects S1,..., S11.

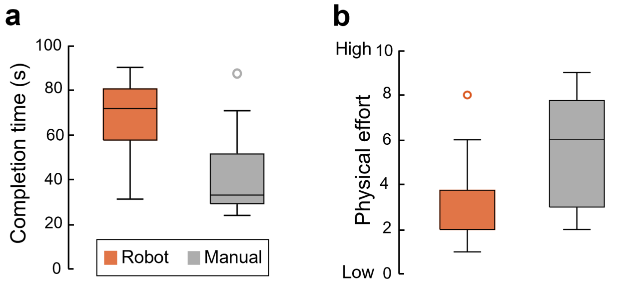

Fig. 8. Result of the suture task. (a) completion time and (b) perceived physical effort.

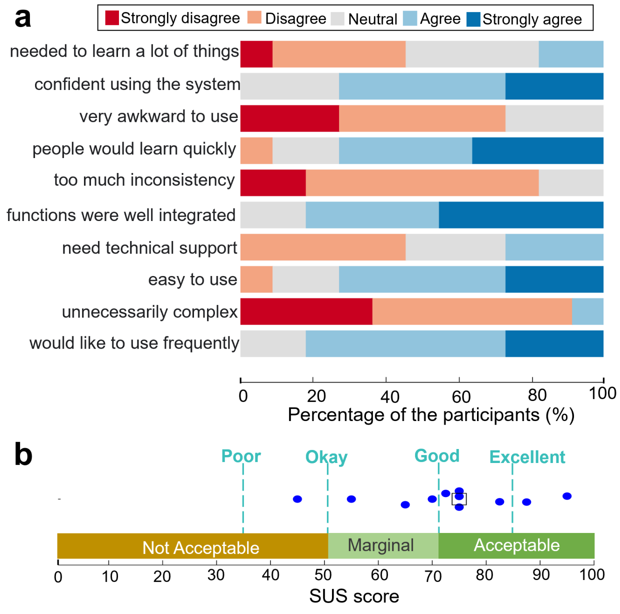

Fig. 9. Result of the SUS questionnaire. (a) Percentage of participants' responses to each question. (b) The SUS score of participants and its median value (blue point represents the SUS score of each participant, black box is the median value).

intuitive and comfortable interaction strategies based on ergonomic hand controllers.

## ACKNOWLEDGMENT

We thank the subjects for participating in the experiment.

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