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Title: A Robotic Microsurgical Forceps for Transoral Laser Microsurgery

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Abstract:

Purpose: In Transoral Laser Microsurgery (TLM), the close curved cylindrical structure of the laryngeal region offers functional challenges to surgeons who operate on its malignancies with rigid, single degree-of-freedom (DOF) forceps. These challenges include surgeon hand tremors, poor reachability, poor tissue surface perception, and reduced ergonomy in design. The integrated robotic microsurgical forceps presented here, is capable of addressing the above challenges through tele-operated tissue manipulation in TLM.

Methods: The proposed device is designed in compliance with the spatial constraints in TLM. It incorporates a novel 2-DOF motorized microsurgical forceps end-effector, which is integrated with a commercial 6-DOF serial robotic manipulator. The integrated device is tele-operated through the haptic master interface, Omega.7. The device is augmented with a force sensor to measure tissue gripping force. The device is called RMF-2F, i.e., robotic microsurgical forceps with 2-DOF end-effector and force sensing.

RMF-2F is evaluated through validation trials and pick-n-place experiments with subjects. Furthermore, the device is trialled with expert surgeons through preliminary tasks in a simulated surgical scenario.

Results: RMF-2F shows a motion tracking error of less than 400μm. User trials demonstrate the device's accuracy in task completion and ease of manoeuvrability using the Omega.7 through improved trajectory following and execution times. The tissue gripping force shows better regulation with haptic feedback (1.624 N) than without haptic feedback (2.116 N).

Surgeons positively evaluated the device with appreciation for improved access in the larynx and gripping force feedback.

Conclusions: RMF-2F offers an ergonomic and intuitive interface for intraoperative tissue manipulation in TLM. The device performance, usability, and haptic feedback capability were positively evaluated by users as well as expert surgeons. RMF-2F introduces the benefits of robotic teleoperation including, (i) overcoming hand tremors and wrist excursions, (ii) improved reachability and accuracy, and (iii) tissue gripping feedback for safe tissue manipulation.

Keywords: Robot-assisted microsurgical forceps; robotic teleoperation; tissue gripping haptic feedback; robotic medical instruments; minimally invasive surgery; transoral laser microsurgery.

1. INTRODUCTION

Transoral Laser Microsurgery (TLM) is a non-invasive surgery for the treatment of laryngeal malignancies, e.g., cysts, polyps, nodules, or cancerous tumours. Introduced by Jako et al. [1], the traditional technique, as seen in Fig. 1(a), involves inserting a laryngoscope (length = 180mm, cross-section 16 X 23mm^2) into the patient's mouth to expose the surgical site. This allows a direct line-of-sight for the surgical microscope. A laser micro-manipulator, consisting of a beam-splitter mirror and a small mechanical joystick, is coupled to the surgical microscope. The free-beam CO_2 surgical laser is aimed manually at the site by moving the mirror. Additionally, manually handled microsurgical instruments allow intraoperative tissue manipulation and extraction.

1.1 Problem Formulation

The manual microsurgical instruments in traditional TLM have scissor-like handles for open-close operation. The most common instrument, the microsurgical forceps (micro-forceps), is used for: (i) tissue manipulation (grasping, orienting, removing); (ii) stretching tissue for precise laser cutting and ensuring minimal thermal damage to healthy tissue; and (iii) orienting tissue to view pathologies. Figure 1(b) shows the dimensions of the various components within the TLM setup. As is seen, within the standard 400mm laser focal distance between the base of the microscope and the surgical site, a narrow 50~100mm range is available for inserting and manoeuvring the micro-forceps. Furthermore, these tools being rigid shaft cause: (i) constrained accessibility in the laryngeal region; (ii) unstable handling due to hand tremors and wrist excursions; and (iii) poor tissue gripping perception. This makes their usage cumbersome and non-ergonomic [2,3].

To overcome the above-mentioned limitations, robotic assistance has been introduced in laryngeal surgery [4]. Towards this end, Simaan et al. [5] presented snake-like manipulators having tip dexterity for tissue manipulation and suturing. Wang et al. [6] presented a robot-assisted master-slave system consisting of two symmetrical 9 degrees-of-freedom (DOFs) cable-driven manipulators, with quick-change interfaces for surgical tools. Solares and Strome [7] and Desai et al. [8] explored the utility of the *da Vinci Surgical System* [4] but found the size of the *da Vinci* tool shafts as a major limitation. These endeavours seek to replace the microscope with dedicated instrument arms entering through the laryngoscope. Importantly, although targeted at laryngeal surgery, the above systems cannot be used in TLM, since there would be no available access for the free-beam laser. He et al. [9] overcame this drawback through their cooperatively controlled teleoperation robot. In this approach, the

instruments can be directly attached / detached from the 3-DOF wrist of the robot itself. Their design serves as an important guidepost for the research in this paper.

On a related note, tissue haptic perception is widely considered to be valuable for robot-assisted surgical procedures, showing enhanced perception accuracy, decreased completion times, and decreased peak and mean applied forces [10]. In TLM, given that the thickness of the laryngeal tissue is about 3~5mm [1], especially in the vocal cords, the regulation of tissue gripping forces is critical in avoiding tissue trauma or rupture. The lack of gripping force feedback is also a limitation with He et al. [9].

With the above background, the goal of this article is the introduction of robotic micro-forceps in TLM with a suitable haptic handling interface.

1.2 Contributions

Previously, in [11], the authors presented a first robotic micro-forceps prototype, which was bulky and unusable under the TLM microscope. In [12], a second version was designed, having a motorized 1-DOF end-effector, which complied with the constraints of TLM and was integrated with a force sensor. Its haptic master interface provided teleoperation control through gesture scaling and elimination of hand tremors and wrist excursions [12]. The haptic feedback facilitated better regulation of gripping force application [12]. Taking this previous research forward, this article presents the design of an improved version of the robotic micro-forceps device, having:

(i) a motorized 2-DOF micro-forceps end-effector, with gripper jaw open/close and tool-shaft rotation for enhanced reachability. The previous version in [12] was only 1-DOF;

(ii) teleoperation control similar to [11];

(iii) tissue gripping force (TGF) capability with impedance-based feedback (as opposed to proportional feedback [12]) for improved tissue surface perception; and

(iv) updated experimental evaluation including phantom tissue-based test-bed along with preliminary validation with expert surgeons, which was not done in [12].

The 2-DOF end-effector, integrated with a commercial 6-DOF serial manipulator arm (UR5 [13]) and the force sensor (ATI Nano17 [14]), forms the RMF-2F, i.e., robotic microsurgical forceps with 2-DOF end-effector and force feedback, as seen in Fig. 2(a). The device is configured to be a 5-DOF setup: 3-DOF Cartesian positioning at the surgical site combined with the 2-DOF end-effector. The RMF-2F is controlled by a haptic master device under unilateral teleoperation through the Omega.7 haptic master interface [15]. The following sections discuss the design, analysis, and evaluation of the proposed device.

2. DESIGN OF THE MOTORIZED 2-DOF MICRO-FORCEPS END-EFFECTOR

Figure 1(b) points to the key dimensions in TLM while Table 1 lists the key features, which are considered in the design of the motorized 2-DOF end-effector. The values for these features are arrived at empirically through measurements of the traditional setup and discussions with expert surgeons. Any mechanism to be used under the microscope, in-line with the surgical line-of-sight, and parallel to the laser beam, would need to have a small thickness to avoid vision occlusion and interference with the laser. Consequently, any actuators for the motorized DOFs would have to be placed away from the line-of-sight. Features 1 and 2 in the Table are therefore, derived from the dimensional constraints of TLM.

The main components of the 2-DOF micro-forceps are the: (i) tool shaft, (ii) tool shaft holder, and (iii) tool actuation mechanism.

2.1 The Tool Shaft

The traditional tool shaft has an outer diameter of ϕ = 2mm with an inner translating wire (*itw*, ϕ = 1mm). The translation of this wire by 3mm (determined experimentally) provides the open-close DOF for the tool jaws. To adapt it, the proximal end of the shaft is modified by attaching a hollow extension tube with external M3 threading to it. This modification is termed as the docking interface (DI) (Refer Fig. 3). The *itw* passes through the hollow DI to attach to the tool actuation mechanism for the open/close DOF, while the outer shaft attaches to the tool shaft holder.

2.2 The Tool Shaft Holder

Figure 4 shows the design of the tool shaft holder, which supports the tool shaft as well as the tool actuation mechanism. It comprises of three sub-frames: F1, F2, and F3. A housing, H_S, mounted on F1 at P1, supports the tool shaft. H_S houses two small ball bearings B_f and B_r. The DI is held within the bearings to incorporate the rotational DOF. H_S is designed to have a cross-sectional thickness of 8mm.

The sub-frames F1 and F2 are rigidly connected at P2. The sub-frame F3 supports the linear actuator driving the open/close DOF while F2 supports the rotary motor providing the rotational DOF. The mechanisms are explained in the following subsections.

2.3 The Tool Actuation Mechanism

The tool actuation mechanism has two main components: the *Open/Close DOF* and the *Rotational DOF*.

2.3.1 Open/Close DOF

This mechanism is adopted directly from the design in [12]. Figure 5 shows the mechanism consisting of five linkages (L1, L2, L3, L4, L5), designed to provide linear translation of the *itw*. The hinge link L1 is considered as ground. L2 forms the input link along the actuator axis and it transfers direct motion to L3, which in-turn transfers inverse motion to L4 about L1. L4 is directly coupled to the driven link L5, which is attached to the *itw*. The Nanotec L2018 linear actuator, with 30N feed force, drives the open/close DOF.

The detailed mechanism design using the graphical synthesis method is presented in [12]. There are two key insights in the design:

(i) The force sensor is located at L2 with its measurement axis coincident with the actuator axis. The reaction force of the closing of the forceps on tissue is transmitted through the *itw* and the linkages on to the sensor surface, which in-turn outputs a signal in direct proportion to the gripping action.

(ii) As stated in Table 1, the optimal displacement between the tool-base and the microscope line-of-sight is 200mm. Here, through the choices of 50mm and 150mm for the lengths of L3 and L4, the total distance between the tool shaft axis and the actuator axis becomes 200mm. Additionally, the link-length ratio for L4:L3 becomes 3:1. Thus, a 1mm displacement of L2 results in a 3mm displacement of L5 and the *itw*, resulting in the open/close of the micro-forceps jaws.

2.3.2 Rotational DOF

The mechanism for the rotational DOF is implemented as the coordinated motion of three components: (i) Miter Gear assembly (MG); (ii) Spur gear assembly (SG); and (iii) Modified link L5 mechanism (M_{L5}) (Refer Fig. 6).

(i) ***Miter Gear assembly, (MG)***: The tool shaft rotation is made possible through a miter-gear assembly with an outer diameter[1] of 8mm (Refer Fig. 6(a)). The gear G_O is mounted onto a shaft S_O such that it is orthogonal to the tool shaft axis. The axial gear G_A is mounted co-axially with the tool shaft axis and attaches rigidly to the DI of the tool shaft. The miter-gear assembly G_O-to-G_A transfers rotation to the tool shaft through DI.

(ii) ***Spur Gear assembly, (SG)***: The shaft S_O rotates through a low-backlash 1:1 spur-gear assembly (SG_1 and SG_2) (Refer Fig. 6(b)). This assembly transfers the rotary motion of the actuator (R_M, Nanotec

[1] This is within the H_S thickness of 8mm.

SC2018 with 1.8 N-cm torque) to S_O, and thereby to *MG*. An additional ball bearing (B_b) supports the rotation of S_O and reduces the vibrations in the rotation.

(iii) ***Modified link L5 in the open/close DOF, (M_{L5})***: To allow simultaneous rotation and translation of the *itw* (through the DI), a suitable adaptation is necessary in link L5. Three components are introduced for this purpose: (i) a specially designed holder (H_I) with set-screws to attach the *itw*. The holder includes a small shaft extension; (ii) this extension is inserted into a small ball-bearing (B_S), thereby allowing H_I to rotate freely; (iii) B_S is held within a housing H_B which is integrated with link L4 (Refer Fig. 6(c)).

With these adaptations, the motorized micro-forceps has 2-DOFs in compliance with the TLM constraints.

3. INTEGRATION OF THE ROBOTIC MICRO-FORCEPS – RMF-2F

As seen in Fig. 2, the 2-DOF motorized micro-forceps tool is attached as an end-effector to the UR5 robotic manipulator at a 90^o angle, resulting in the RMF-2F device. The UR5, seen in Fig. 2(b), has a payload capacity of 5 kg, repeatability of 0.1mm, a reach radius of 850mm, and can be controlled at 125 Hz. These values make it suitable for precise teleoperation control. Since the motorized micro-forceps already has a rotational DOF, the final orientation DOF of the UR5 is not used. The D-H parameters of the integrated RMF-2F device are suitably updated as a 5-DOF global device (3-DOF positioning + 1 DOF rotation + 1 DOF open/close), as given in Table 2.

4. TELEOPERATION CONTROL AND VALIDATION

A master haptic interface, the Force Dimension Omega.7, as seen in Fig. 2(d), teleoperates the RMF-2F. The Omega.7 has 7-DOFs (6-DOF motion + 1-DOF gripper), of which the three translational DOFs and the gripper DOF are active. The three translational DOFs control the 3-DOF positioning of the RMF-2F. The *yaw* DOF of the Omega.7 commands the rotational DOF of the RMF-2F, while the gripper DOF commands its open/close. Omega.7 provides active gravity compensation to improve the teleoperation transparency and reduce the operator's fatigue. The integrated system uses a dedicated gigabit Ethernet connection between the master and the RMF-2F device, ensuring minimal time delay between the two. A two-layer, time-domain controller [16] preserves the stability and transparency of the system.

(i) Since the kinematics of the master interface and the RMF-2F are non-homothetic, a unilateral velocity-based teleoperation controller is implemented. This was suitable for the requirements of the narrow

workspace inside the laryngoscope. The 3-DOF master end-effector velocity ($\dot{q}_h \in \mathbb{R}^3$) is filtered and scaled with a gesture scaling factor ζ and mapped to the velocity ($\dot{q}_r \in \mathbb{R}^3$) of the RMF-2F, as shown in Eq. 2. The constants have values: ζ = 0.2 and β = 0.025, adapted from [11].

$$\begin{aligned} \dot{q}_h^k &= (1-\beta)\cdot \dot{q}_h^{k-1} + \beta \cdot \dot{q}_h \\ \dot{q}_r^k &= J^{-1}\cdot \dot{q}_h^k \cdot \zeta \end{aligned} \qquad (2)$$

J^{-1} is the inverse of the manipulator Jacobian matrix, $J \in \mathbb{R}^{3x3}$. The integrated system was characterized in [11] giving a low position mapping error of 0.3901mm ± 0.3829mm, signifying transparency and accuracy. Figure 7(a) shows a sample plot for the tracking error in one axis.

(ii) For the end-effector, the jaw open/close and tool-tip rotation are controlled unilaterally. The relationship is shown by Eq. 3, where η_1 = 3 and η_2 = 2 are empirically chosen to compensate for the friction and hysteresis in the system. The position command loop runs at 100Hz.

$$\begin{bmatrix} q_{rot} \\ q_{jaw} \end{bmatrix} = \begin{bmatrix} \eta_1 & 0 \\ 0 & \eta_2 \end{bmatrix} \begin{bmatrix} q_h^{yaw} \\ q_h^{grip} \end{bmatrix} \qquad (3)$$

(iii) For force sensing, the ATI Nano17 Force/Torque sensor (Fig. 2(c), ϕ = 17mm, L = 14.5mm), offers a fine resolution of 3.125 mN with sensing up to 70 N, and registering data at 7 kHz. The characterization of the TGF at the sensor was done in [11]. Figure 7(b) shows the TGF value varying non-linearly from the fully open position of the micro-forceps (0N, tissue not touching the jaws) to the fully-closed position (16N). The inset in Fig. 7(b) shows the customized characterization setup.

5. EXPERIMENTAL EVALUATION

The performance of the RMF-2F device was validated through evaluation experiments simulating real surgical actions like grasping, pulling, and manipulating the laryngeal tissue. These trials were performed with 10 non-medical subjects (mean age = 28.2 years; 8 males, 2 females) with no prior experience in such tasks. The trials consisted of pick-rotate-n-place tasks, as seen in Fig. 8. A test-bed with cavities for different 3D-printed shapes (triangle, rectangle, semi-circle, and circular ring) was prepared. The shapes were fixed with artificial tissue-like material to provide tissue-gripping sensation. This phantom tissue is a bi-component polyurethane elastomer (F-105 A/B 5 shore, BJB Enterprise) added with a softening agent (SC- 22, BJB Enterprise) [17]. For uniformity of results, each trial began with the RMF-2F in home position (15mm above the test-bed center). The experiments were conducted in two conditions, C1 (haptic feedback activated) vs. C2 (haptic feedback deactivated).

In condition C1, the measured TGF is rendered to the gripper DOF of Omega.7. To do this, the force sensor value is first filtered using a low-pass filter (β = 0.001, Eq. 4), to suppress noisy signals. It is then scaled based on the internal angle of the micro-forceps jaws using Eq. 5. The value rendered to the gripper DOF is calculated using Eq. 6. Here, Ω_g is the maximum internal angle of the jaws in open position, i.e., 90°, and ω_g^k is the internal angle at instant *k*. After extensive offline testing, the values of the constants were obtained as $c = 1.5$ and $\gamma = 1/20$, giving $1.5 < k^k < 5.5$. The rendered force therefore varies in proportion to the sensed force as well as the internal angle of the gripping jaws, giving an impedance-based haptic feedback.

$$f_g^k = (1 - \beta).f_g^{k-1} + \beta.f_g^{sensor} \quad (4)$$

$$k^k = \gamma.\left(\Omega_g - \omega_g^k\right) + c \quad (5)$$

$$f_g^{omega} = \begin{cases} 0, & f_g^k \leq 0 \\ k^k \cdot f_g^k, & f_g^k > 0 \end{cases} \quad (6)$$

f_g^{sensor} is calibrated to avoid the values from the free-space open/close of the RMF-2F. The haptic feedback loop runs at 500Hz to ensure transparency. Figure 9 shows the behaviour of Eq. 6 for ω_g^k, f_g^k, and f_g^{omega} with a sample trial with the Triangle shape. As is seen, f_g^k varies between -1 and 2 N, while f_g^{omega} varies between 0–10 N, through the various phases of: closed jaws (0° angle), micro-forceps opening ('A'), shape gripped ('B'), shape release initiated ('C'), and shape released ('D').

Subjects conducted 8 trials each (twice on each shape) in the following order: (i) Semi-circle, (ii) Ring, (iii) Triangle, and (iv) Rectangle. The conditions C1 and C2 were randomized across the trials to obtain un-biased evaluation. The device performance was analysed by measuring the: (i) Trajectory followed by the RMF-2F for the tasks; (ii) Execution time required to conduct the tasks; (iii) Number of failed attempts during task execution; and (iv) TGF feedback performance in C1 and C2 conditions.

5.1 Trajectory Analysis

Figure 10(a) shows a sample trajectory for the RMF-2F with the Triangle shape, starting from the home position, picking-up the object from its cavity, and then placing it in the other cavity. The re-orientation of the objects during the trial is quantified (180° in case of the Triangle) in Fig. 10(b), where the radial direction represents the time in seconds. For analysing the usability of the device, the trajectory ratio was used as a metric. With 8 consecutive trials, the trajectory length for the first trial was used as the basis against which the ratios for the 7 succeeding trials were calculated. Figure 11(a) shows the overall trend of the ratios over time indicating that the subjects find the device easy and quick to learn. The ratio of the 8th-to-1st trial is 0.6988, while the average

ratio over the 7 trials is 0.9111. The positive performance for the device is attributed to the ease-of-learning offered by the Omega.7 interface and its transparent integration with the RMF-2F.

5.2 Execution Time and Controllability

A similar downward trend in the time taken for the task completion demonstrates the RMF-2F's ease-of-learn-ability. Figure 11(b) shows such trends for the two metrics: (i) time to lift the shape from the cavity (T_{lift}); and (ii) time to transfer the shape (T_{total}). As observed, T_{lift} goes from 43.2s to 28.8s, an improvement of 33.3%. The same trend is seen for T_{total}, going from 84.2s to 49.9s, giving an improvement of almost 40%.

In terms of controllability, over all the trials (a total of 80), only 18 failed attempts (failure to lift the shape or transfer it to the other cavity) were recorded in task execution.

5.3 Tissue Gripping Force analysis

TGF feedback analysis was conducted using the f_g^k value from Eq. 6. Figure 12(a) shows a sample trial for the Triangle shape in the C1 and C2 conditions, where the difference in levels of force is evident. The highlighted locations indicate phases of the task. The analysis shows that the average TGF applied on the phantom tissue is less in condition C1 (1.624 N) in comparison to C2 (2.116 N), as seen in Fig. 12(b). This difference is statistically significant according to the *Student's t-test* ($p = 0.0486$). Similarly, the value for the maximum TGF is less in C1 (5.532 N) than in C2 (6.768 N), although not statistically significant ($p > 0.05$). For soft tissue, the closing of the RMF-2F jaws displaces the tissue around the jaws, thereby causing a non-linear variance (and reduction) in the gripping force over time. By incorporating the internal jaw angle in the force feedback, this effect of squeezing soft tissue can be compensated for, providing a more natural tissue gripping sensation. This demonstrates better regulation of gripping forces in the C1 condition, where the subjects applied less force on the phantom tissue, as against the C2 condition. It allows better tissue surface perception and improved safety against potential tissue trauma.

Furthermore, in terms of controllability, out of the 18 failed trials recorded, 8 were in the C1 condition and 10 in the C2 condition. Although positive for C1, this data is not conclusive enough.

5.4 Preliminary Surgeon Trials

To introduce RMF-2F in the TLM operating room (OR), it is important to understand the suitability of its functionality and features for the surgeons. In this regard, three surgeons from the Ospedale San Martino in

Genova (Italy) were invited to perform preliminary experiments using the RMF-2F device. To simulate real surgery, ex-vivo pig larynxes, held in a specially designed holder, were used. Pig larynxes, available at the supermarket, resemble the human larynx closely and surgeons use them frequently for training purposes [18]. The surgical setup, with surgical microscope, laryngoscope, laser micro-manipulator, larynx-holder, and the RMF-2F, is seen in Fig. 13. When positioned properly, the pig larynx provides similar constraints as in the real TLM surgery, and thus is an optimal test-bed to evaluate the overall RMF-2F design. The surgeons were asked to perform grasping, pulling, turning, and manipulation of the larynx tissue. The surgeons provided useful informal feedback:

(i) ***Tool-tip rotation***: This functionality was appreciated by the surgeons since it helped them reach different areas of the vocal region. They were able to grip-n-turn the tissue for better exposition.

(ii) ***Appreciation of TGF feedback***: While using the device under two different feedback conditions (C1 and C2), surgeons could distinguish between gripping action on tissues and regulate the applied forces.

(iii) ***Vision occlusion under microscope***: The surgeons complained about partial vision occlusion during usage. This implies the need to further reduce the device dimensions.

6. DISCUSSIONS

The RMF-2F device is a first-of-its-kind device introducing robotic assistance and haptic feedback in TLM, while also complying with the associated spatial constraints. The positive evaluations from the non-medical subjects and surgeons demonstrate that the RMF-2F would be beneficial in the TLM OR. The ergonomics and comfort while controlling the device, tissue perception through haptic feedback, and reachability with the device are key improvements introduced by RMF-2F.

The evaluations pointed to the required improvements as well. The cantilever tool shaft introduced small vibrations at the tip and caused the vision occlusion mentioned by the surgeons. Based on comments by the surgeons, an additional DOF for tip articulation may would allow overcoming these issues through better tip control, while also enhancing accessibility. This re-design is currently under investigation.

The surgeon trials also highlighted the need for training in using a device like the RMF-2F, especially through haptic teleoperation. Years of prior training allows surgeons to use traditional manual tools under the microscope effortlessly. With similar experience, surgeons may be able to easily manoeuvre robotic devices through teleoperation as well.

7. CONCLUSIONS

This paper presented a novel design of the 5-DOF RMF-2F device for intraoperative use in TLM, integrated with the Omega.7 teleoperation haptic master and the ATI Nano17 force sensor. The RMF-2F device offers: (i) motorized tool-tip open/close and rotation; (ii) precise motion, stable positioning, no hand tremors, reduced wrist excursions, and gesture scaling through teleoperation; and (iii) improved safety through tissue gripping haptic feedback.

In future research, along with improvements in device form-factor, the gripping force shall be further investigated for isolating different components like stretching, twisting, etc. The limits of stability and transparency shall also be established for intuitiveness in robotic teleoperation.

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FIGURE CAPTIONS

Fig.1 Traditional TLM surgical setup: (a) overall dimensions; (b) dimensions around the laryngoscope

Fig.2 The 5-DOF "RMF-2F" device. (a) 2-DOF micro-forceps end-effector integrated with the 6-DOF UR5 robot and the ATI Nano17 force sensor; (b) UR5; (c) ATI Nano17; (d) Omega.7.

Fig.3 The tool shaft

Fig.4 The tool shaft holder

Fig.5 The tool actuation mechanism

Fig.6 Detailed view of the rotational DOF of the tool actuation mechanism. (a) Miter Gear Assembly, (MG); (b) Spur Gear Assembly, (SG); (c) Link L5 modification, (M_{L5})

Fig.7 Characterization of the RMF-2F: (a) Motion control evaluation; (b) TGF sensing (Inset: Characterization setup)

Fig.8 Experimental evaluation setup. (a) Subject performing trial; (b) Test bed dimensions; (c) Test bed with phantom tissue shapes

Fig.9 Sample trial depicting behaviour of Eq. 6. The highlighted locations indicate the phases of the trial: 'A' = Micro-forceps opening; 'B' = Shape gripped; 'C' = Shape release initiated; 'D' = Shape release completed

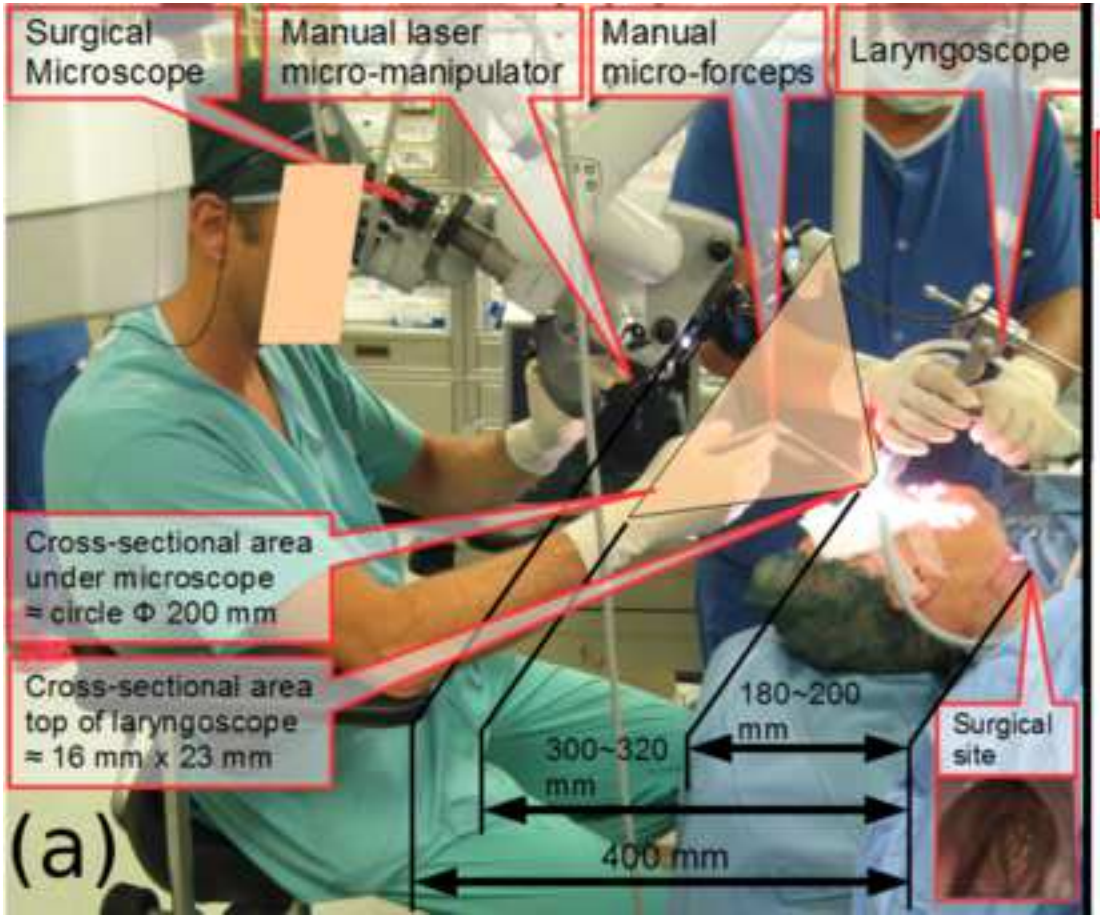
Fig.10 RMF-2F trajectory during a sample trial. (a) 3-DOF position during task; (b) Angular orientation during task

Fig.11 Results of experimental evaluation. (a) Overall trajectory ratio; (d) Execution time

Fig.12 Results of TGF analysis. (a) Difference in TGF values for C1 and C2 condition for a sample trial; (b) Comparison of mean and maximum TGF

Fig.13 Setup for preliminary trials of RMF-2F with expert surgeons

Figure 1


Surgical Microscope
Manual laser micro-manipulator
Manual micro-forceps
Laryngoscope
Cross-sectional area under microscope ≈ circle Φ 200 mm
Cross-sectional area top of laryngoscope ≈ 16 mm x 23 mm
180~200 mm
300~320 mm
400 mm
Surgical site
(a)

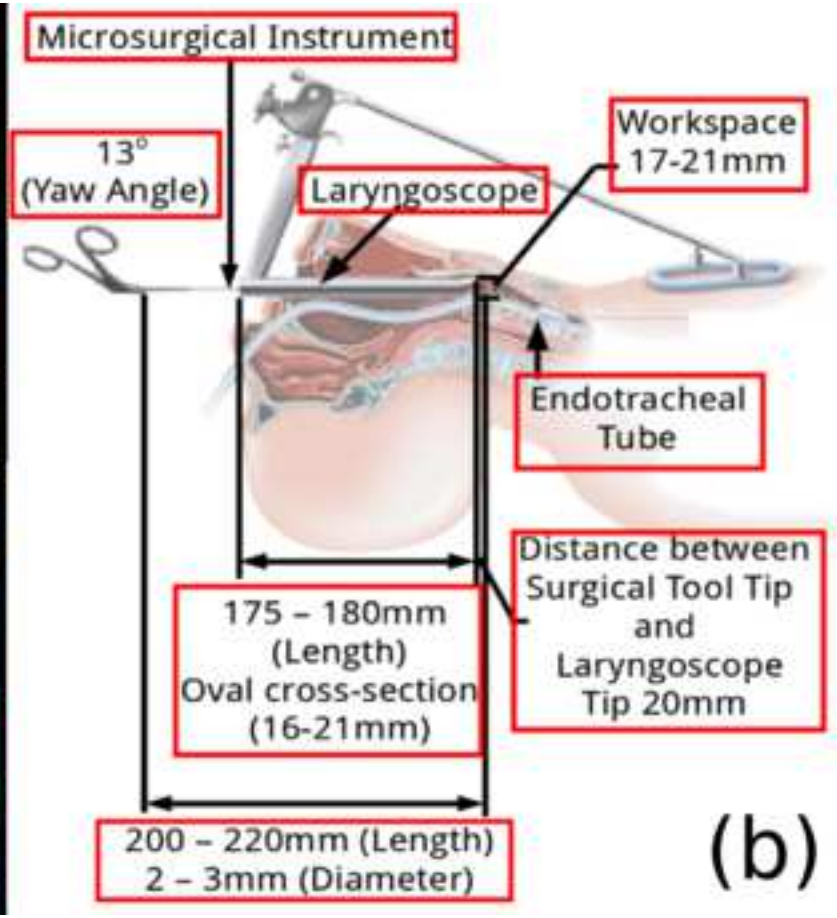

Microsurgical Instrument
13° (Yaw Angle)
Laryngoscope
Workspace 17-21mm
Endotracheal Tube
Distance between Surgical Tool Tip and Laryngoscope Tip 20mm
175 – 180mm (Length) Oval cross-section (16-21mm)
200 – 220mm (Length) 2 – 3mm (Diameter)
(b)

Figure 2

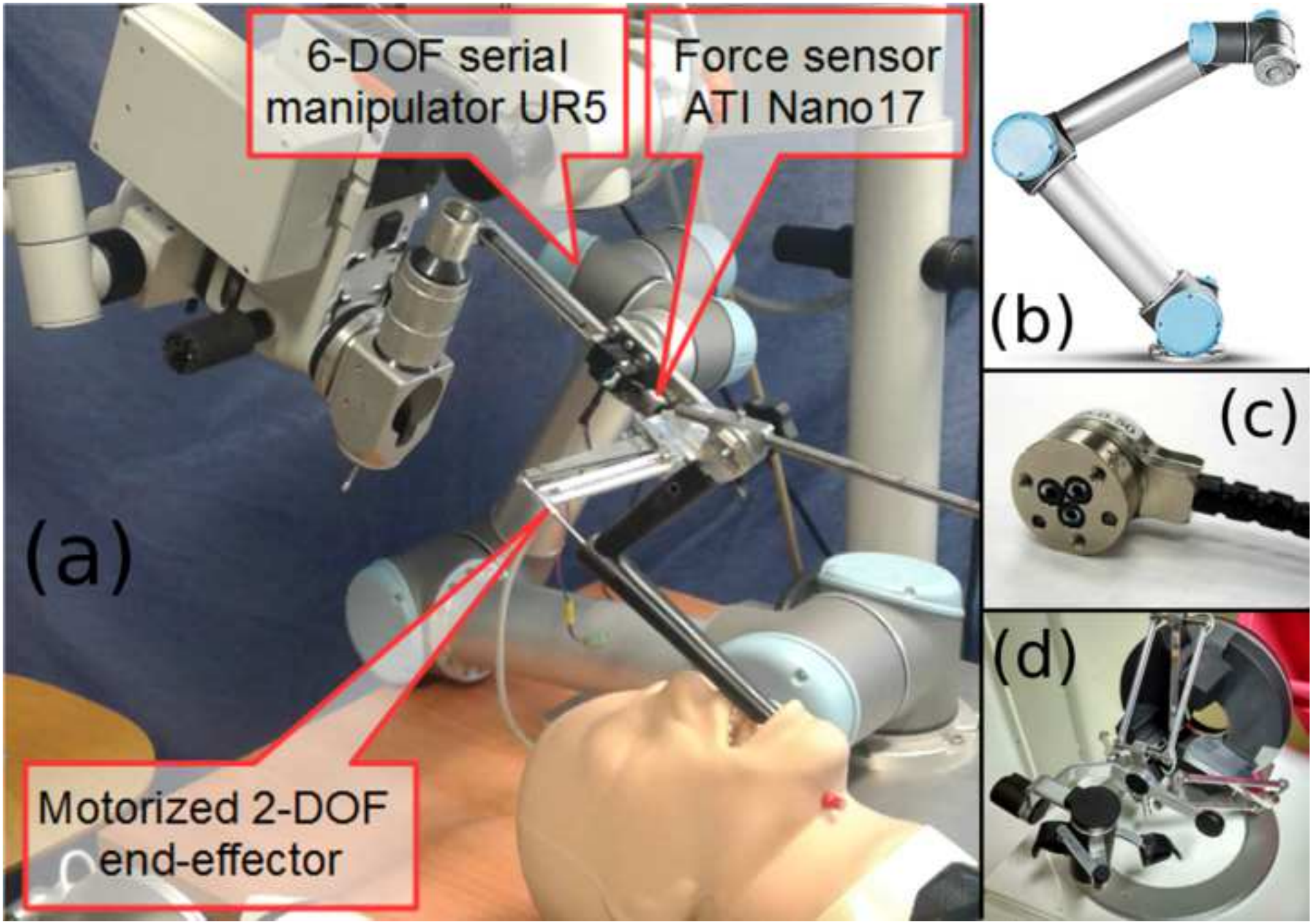

6-DOF serial manipulator UR5
Force sensor ATI Nano17
Motorized 2-DOF end-effector
(a)
(b)
(c)
(d)

Figure 3

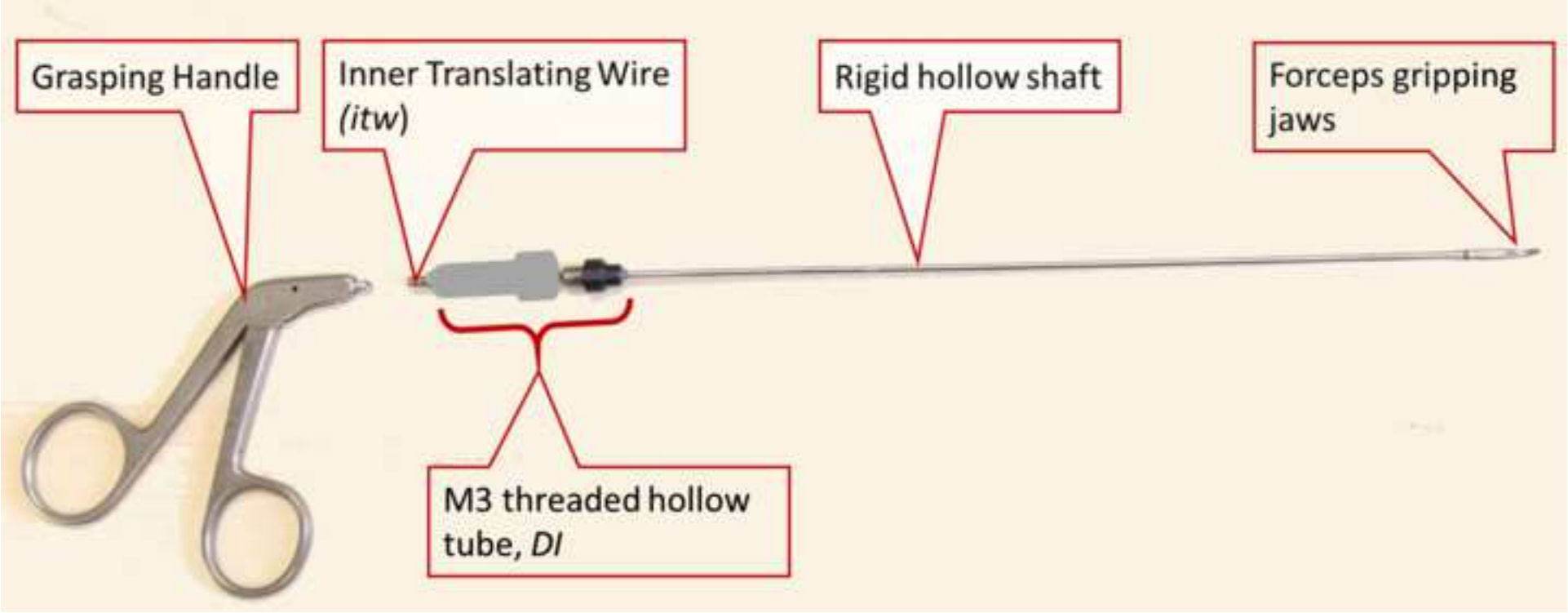

Grasping Handle
Inner Translating Wire (itw)
Rigid hollow shaft
Forceps gripping jaws
M3 threaded hollow tube, DI

Figure 4

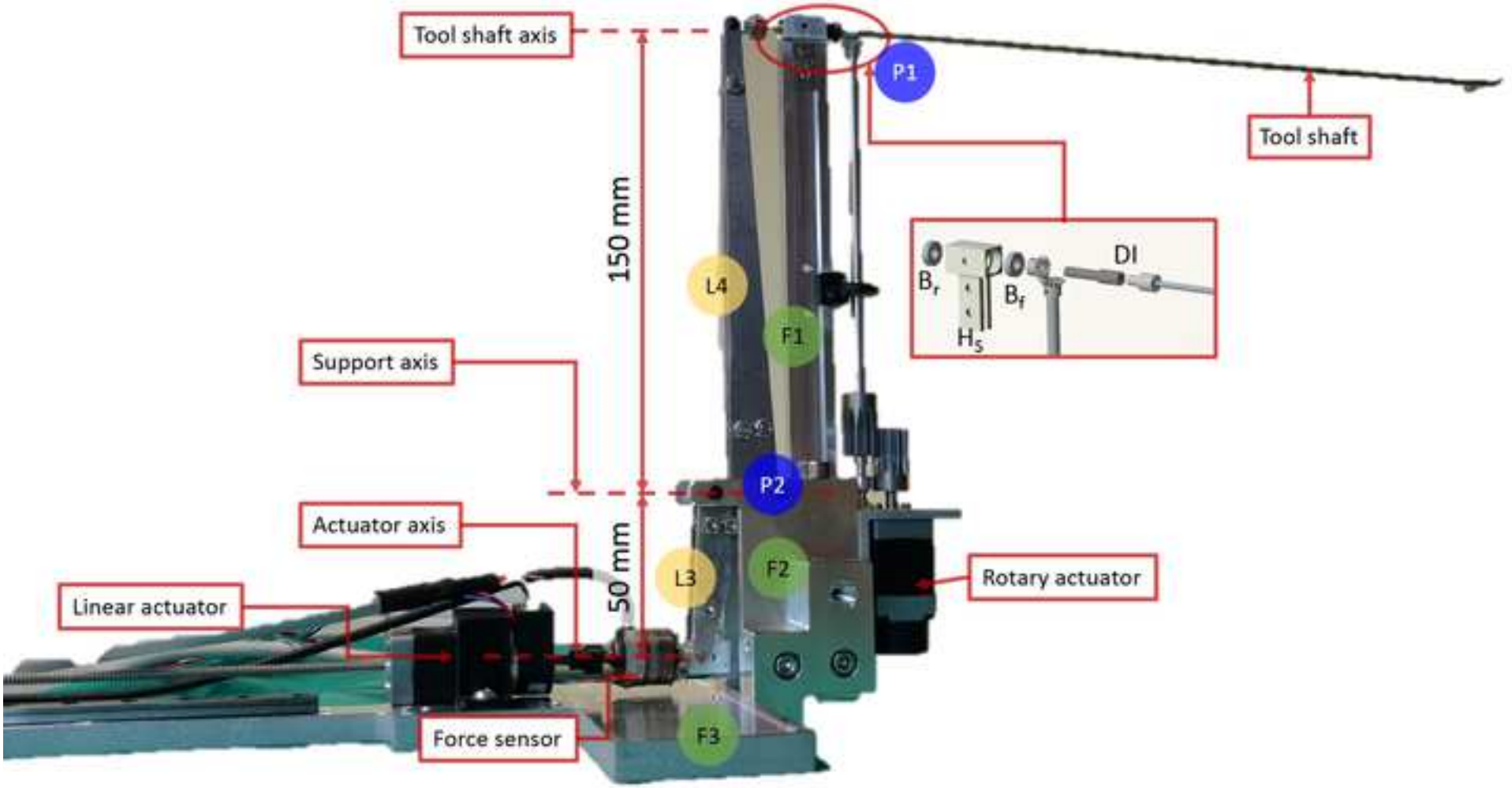

Tool shaft axis
P1
Tool shaft
150 mm
L4
F1
DI
B_r
B_f
H_s
Support axis
P2
Actuator axis
50 mm
L3
F2
Rotary actuator
Linear actuator
Force sensor
F3

Figure 5

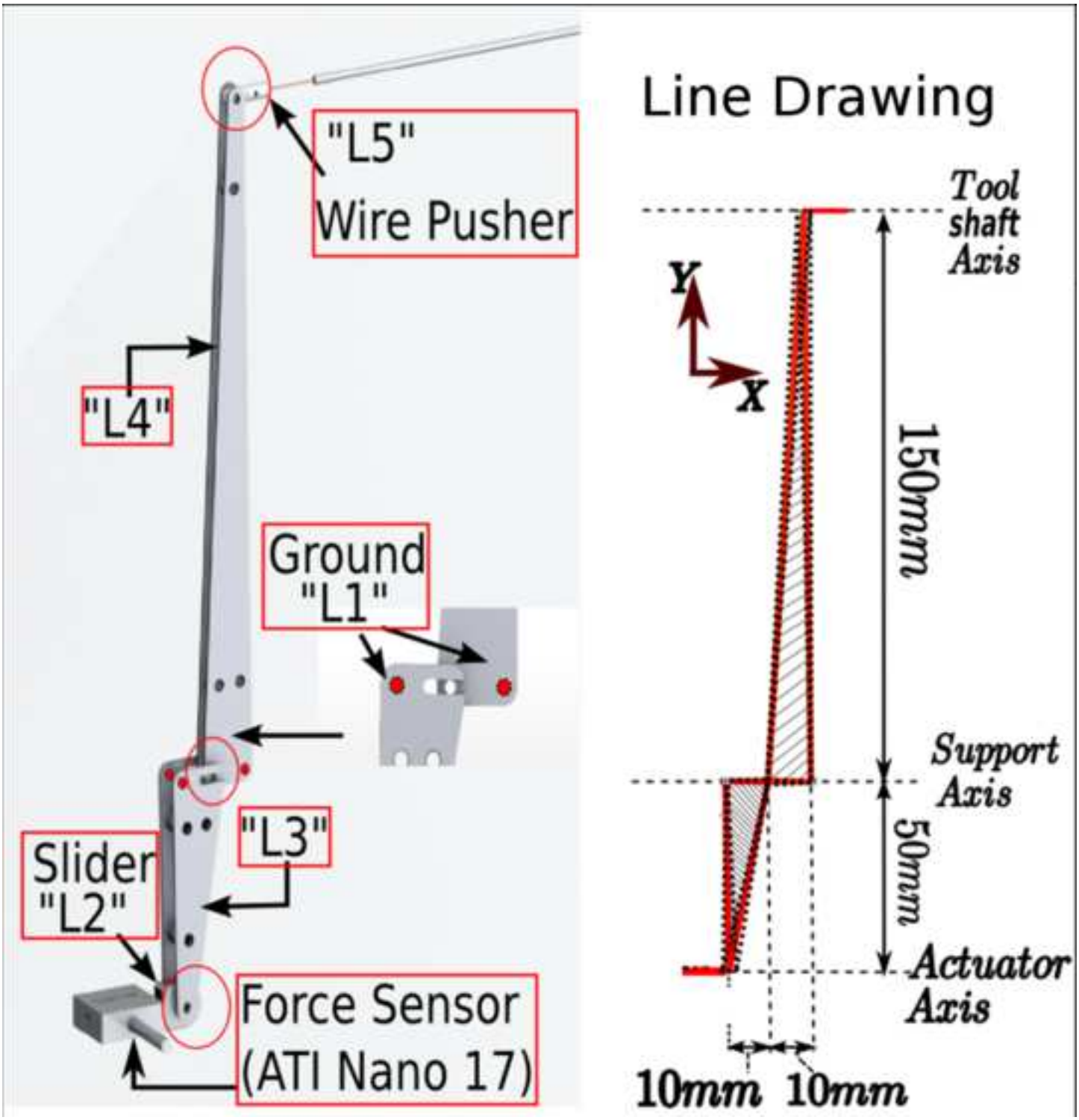

"L5"
Wire Pusher
"L4"
Ground
"L1"
"L3"
Slider
"L2"
Force Sensor
(ATI Nano 17)
Line Drawing
Tool
shaft
Axis
Y
X
150mm
Support
Axis
50mm
Actuator
Axis
10mm
10mm

Figure 6

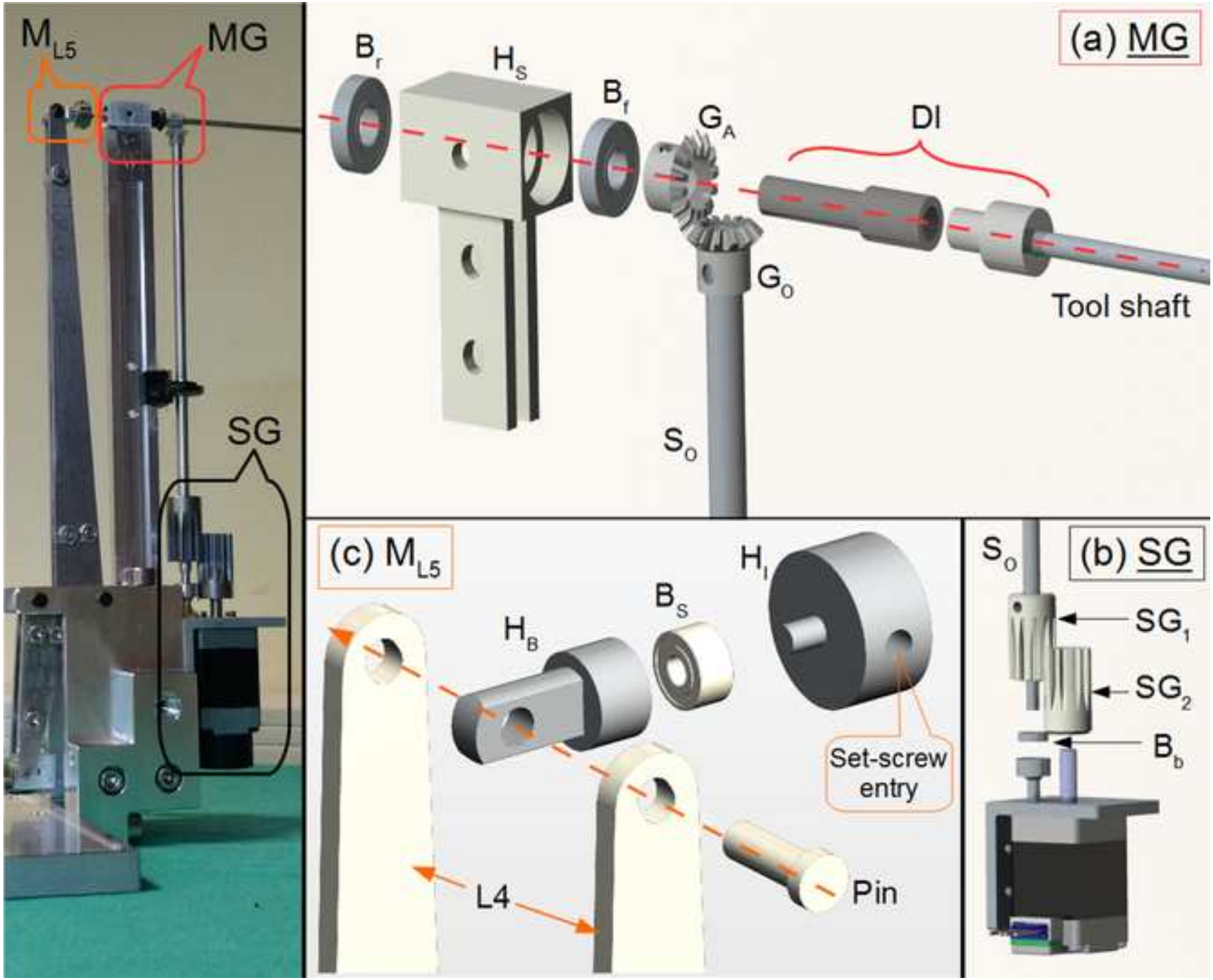

M L5
MG
SG
(a) MG
B r
H S
B f
G A
DI
G O
Tool shaft
S O
(c) M L5
H I
B S
H B
Set-screw entry
L4
Pin
S O
(b) SG
SG 1
SG 2
B b

Figure 7a

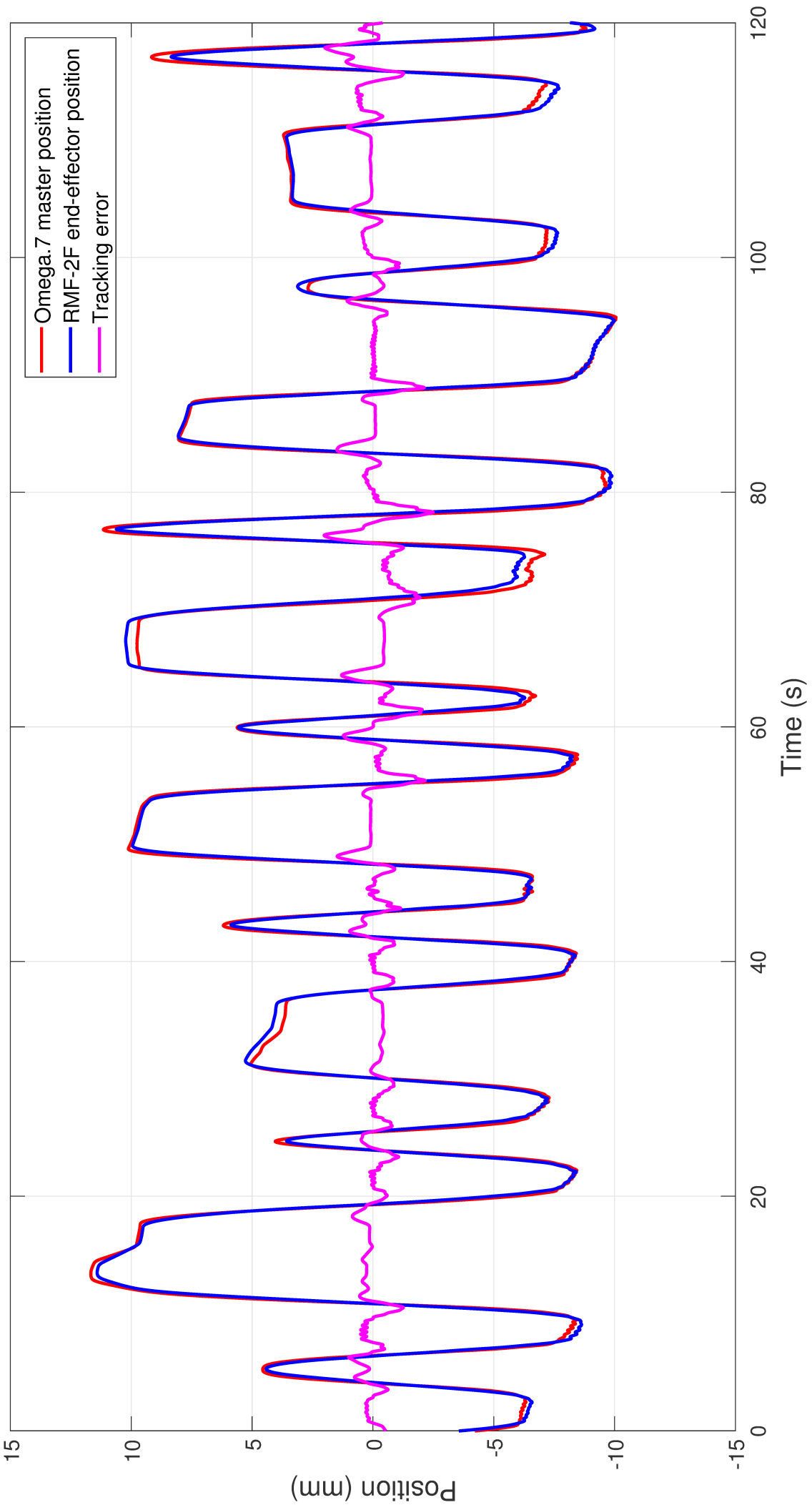

Omega.7 master position
RMF-2F end-effector position
Tracking error
Position (mm)
Time (s)
15
10
5
0
-5
-10
-15
0
20
40
60
80
100
120

Figure 7b

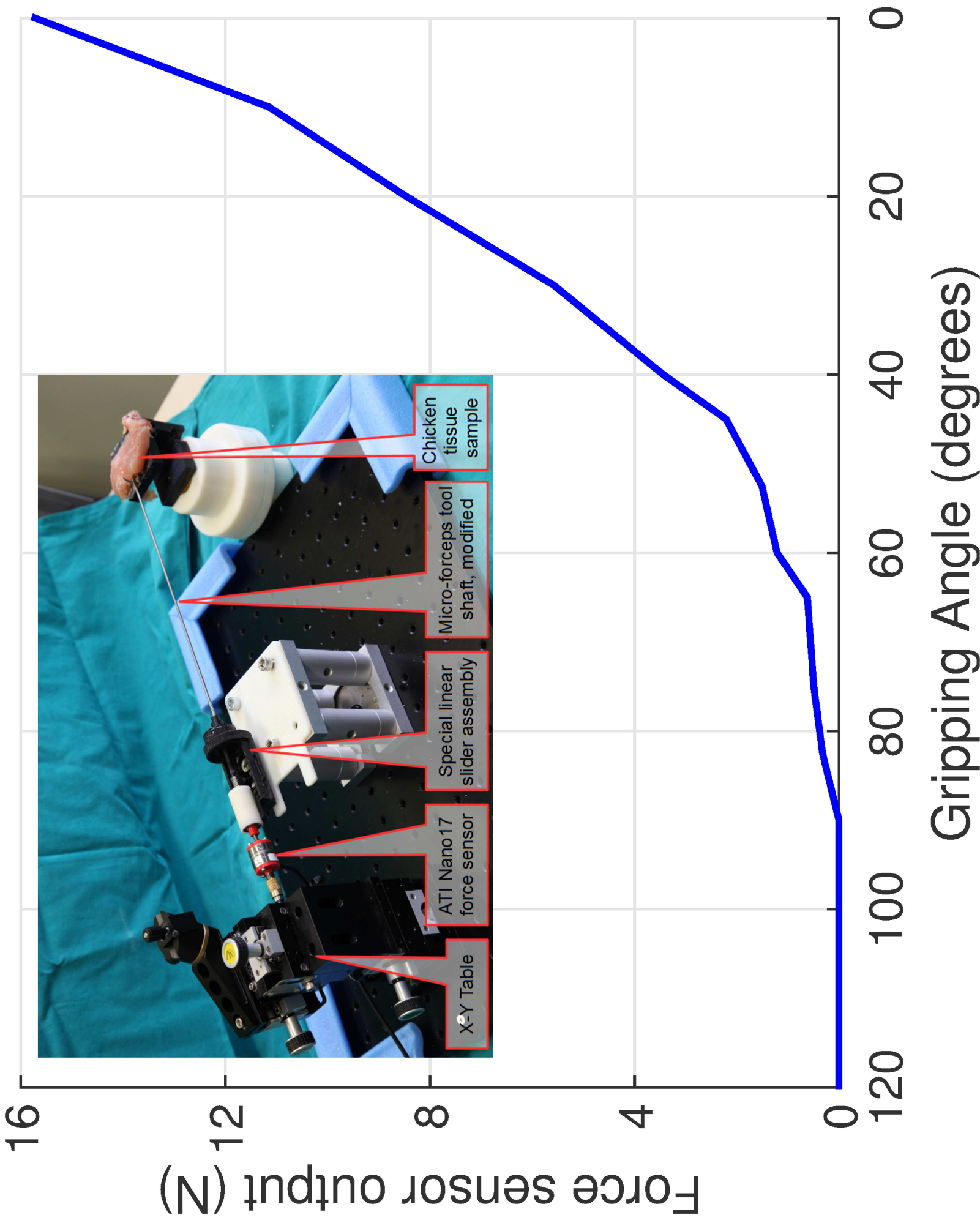

Force sensor output (N)
16
12
8
4
0
120
100
80
60
40
20
0
Gripping Angle (degrees)
X-Y Table
ATI Nano17 force sensor
Special linear slider assembly
Micro-forceps tool shaft, modified
Chicken tissue sample

Figure 8

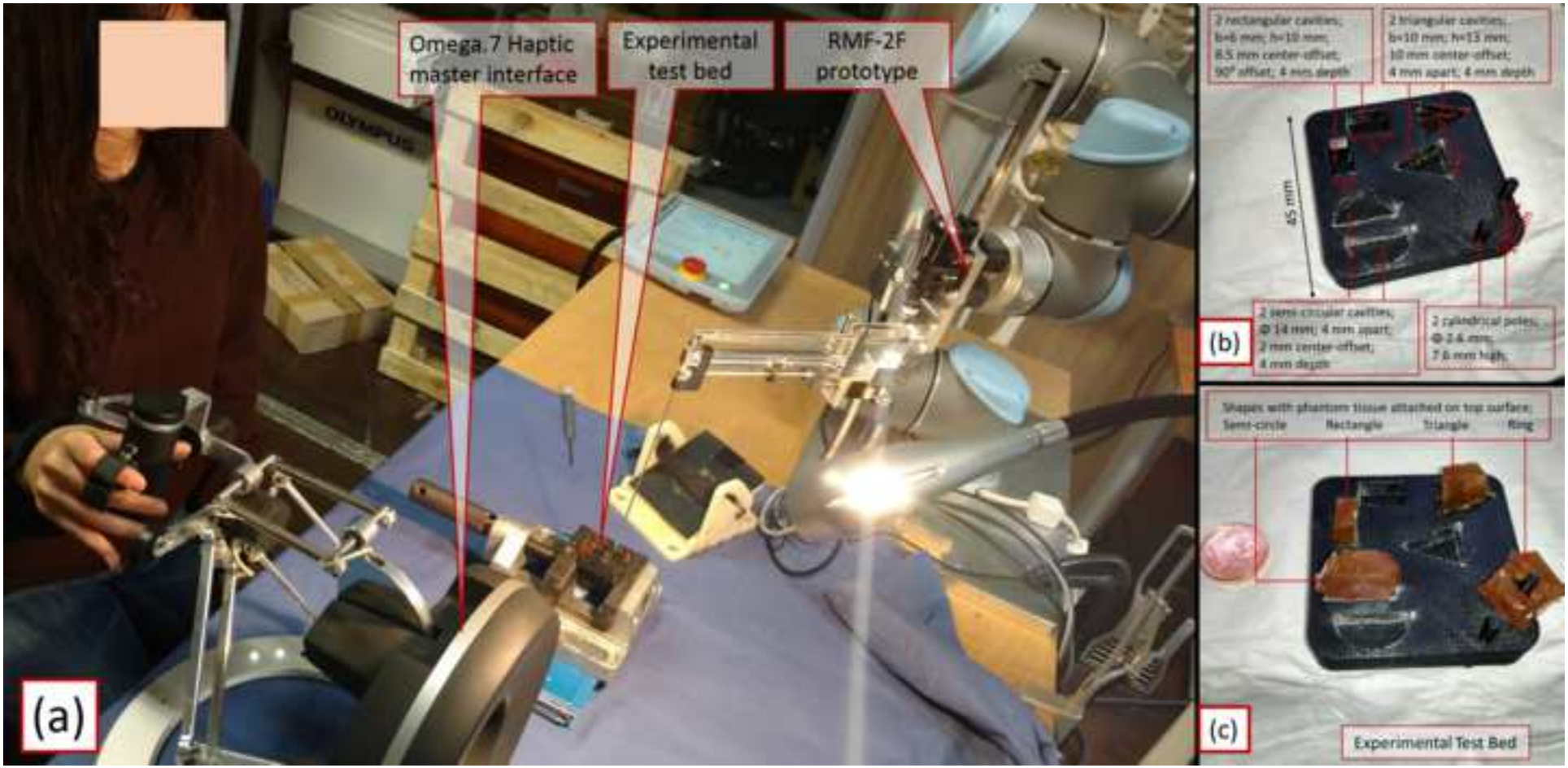

Omega.7 Haptic master interface
Experimental test bed
RMF-2F prototype
(a)
2 rectangular cavities; b=6 mm; h=10 mm; 8.5 mm center-offset; 90° offset; 4 mm depth
2 triangular cavities; b=10 mm; h=13 mm; 10 mm center-offset; 4 mm apart; 4 mm depth
45 mm
(b)
2 cylindrical poles; Φ 2.6 mm; 7.6 mm high
Shapes with phantom tissue attached on top surface:
Semi-circle
Rectangle
Triangle
Ring
(c)
Experimental Test Bed

Figure 9

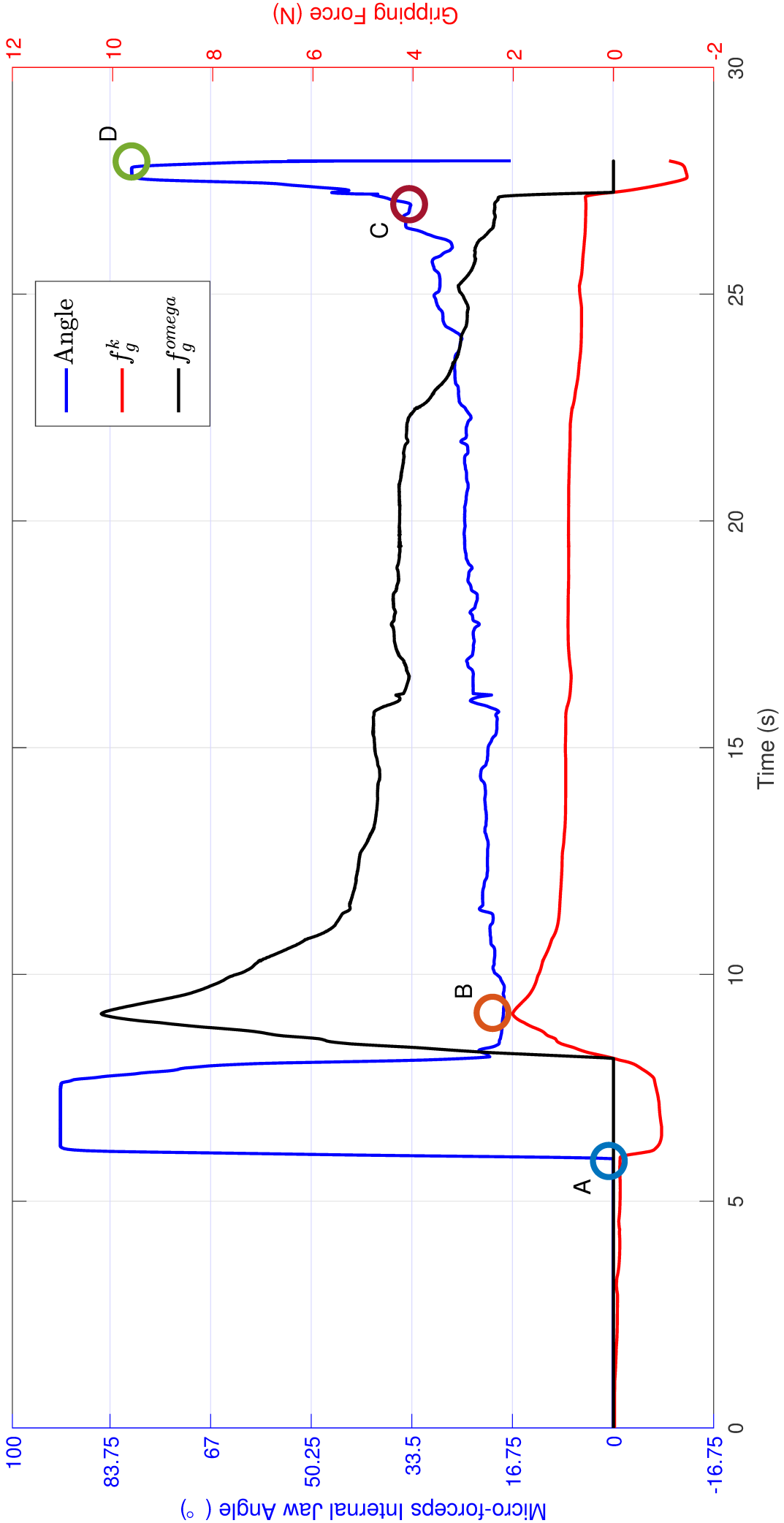

Gripping Force (N)
12
10
8
6
4
2
0
-2
Micro-forceps Internal Jaw Angle (°)
100
83.75
67
50.25
33.5
16.75
0
-16.75
Time (s)
0
5
10
15
20
25
30
A
B
C
D
Angle
f_g^k
f_g^{omega}

Figure 10a

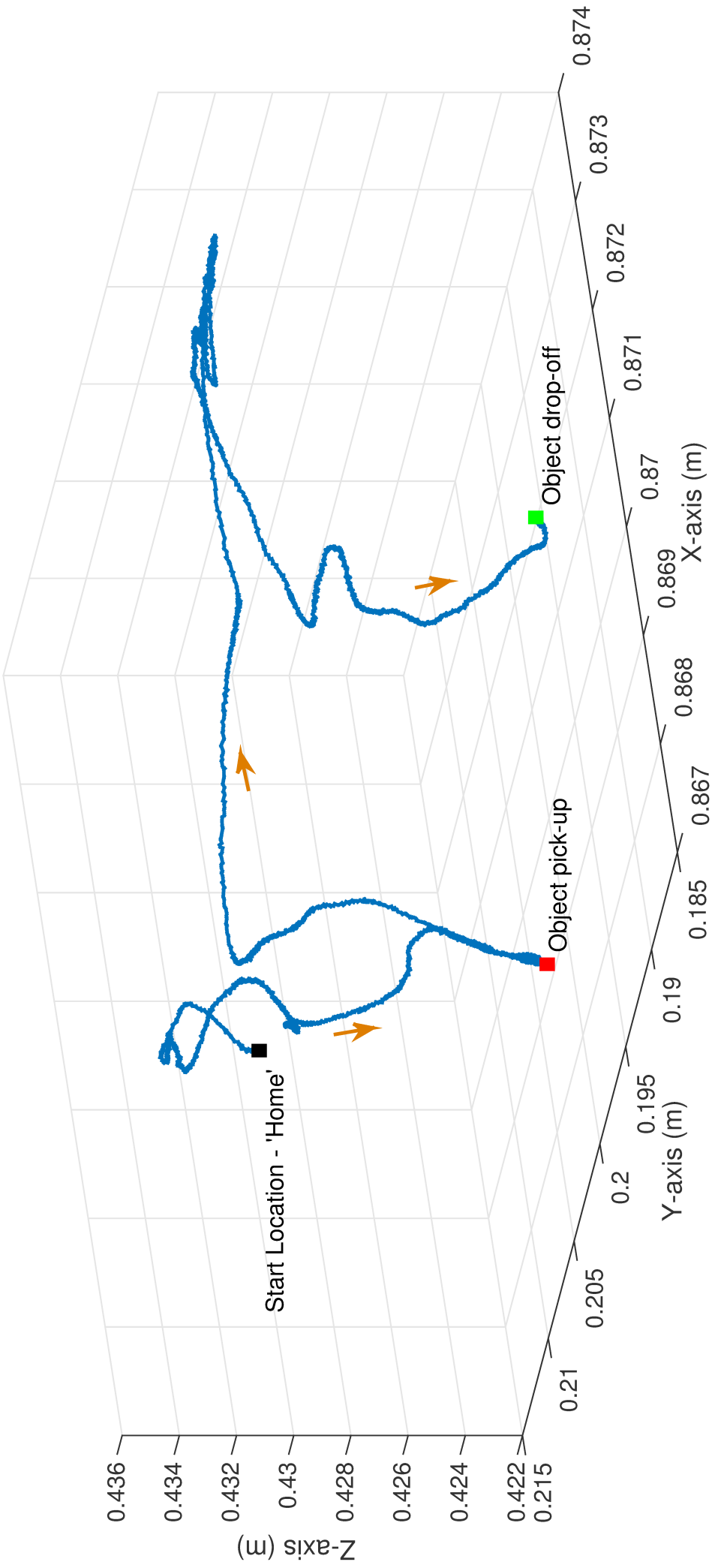

Start Location - 'Home'
Object pick-up
Object drop-off
Z-axis (m)
0.436
0.434
0.432
0.43
0.428
0.426
0.424
0.422
0.215
Y-axis (m)
0.21
0.205
0.2
0.195
0.19
0.185
X-axis (m)
0.874
0.873
0.872
0.871
0.87
0.869
0.868
0.867

Figure 10b

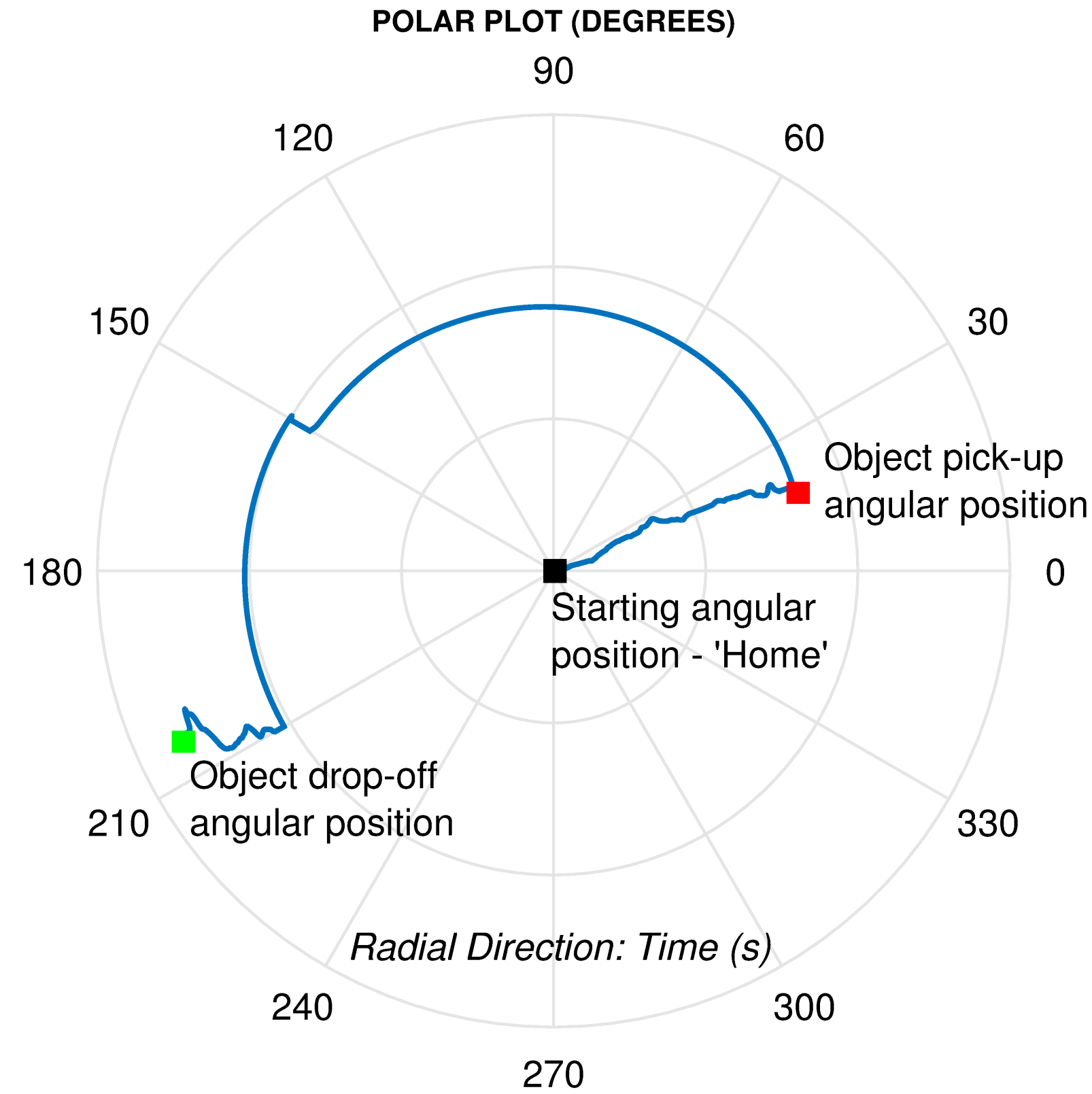

POLAR PLOT (DEGREES)
90
120
60
150
30
180
0
210
330
240
300
270
Object pick-up
angular position
Starting angular
position - 'Home'
Object drop-off
angular position
Radial Direction: Time (s)

Figure 11a

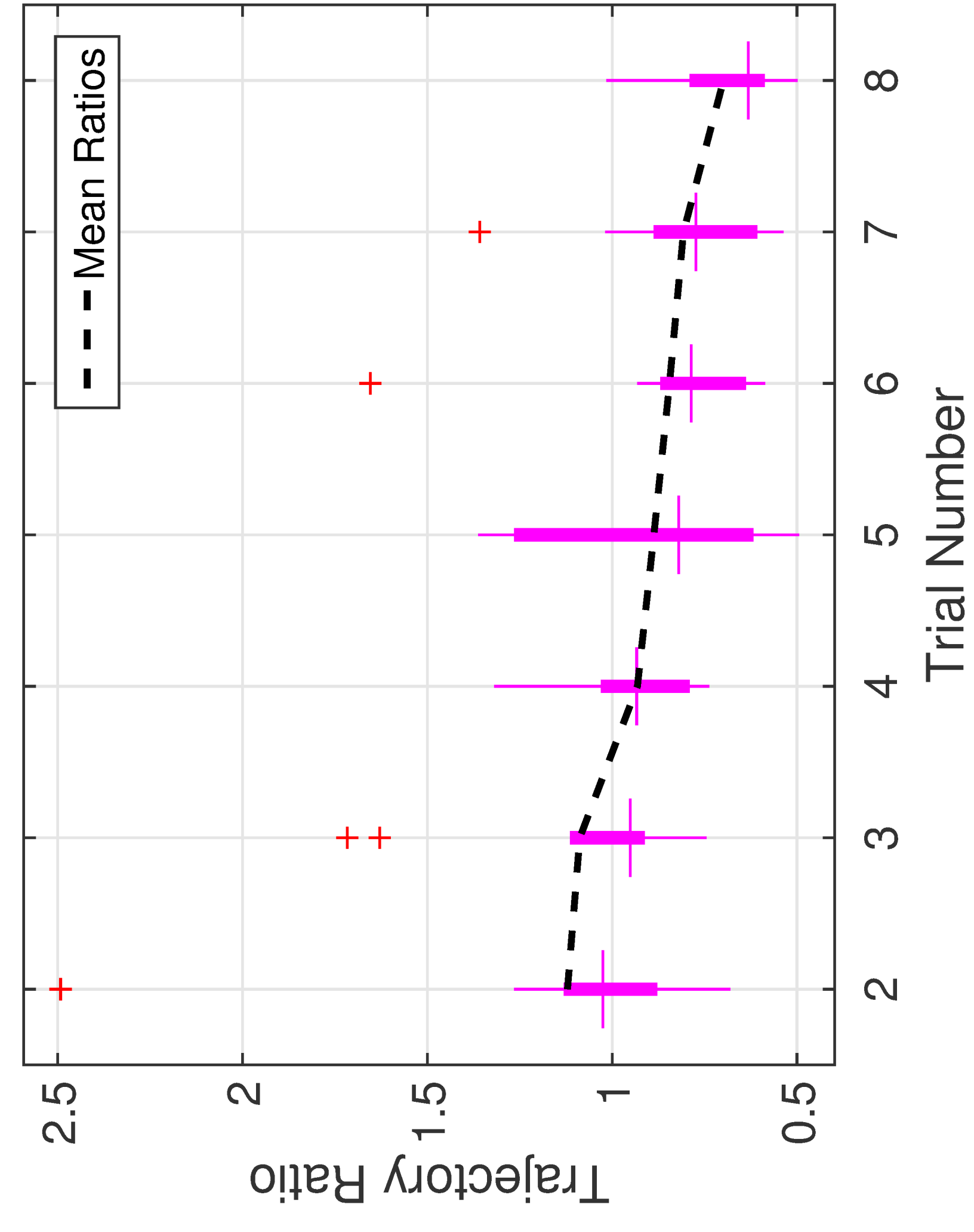

Mean Ratios
Trajectory Ratio
2.5
2
1.5
1
0.5
Trial Number
2
3
4
5
6
7
8

Figure 11b

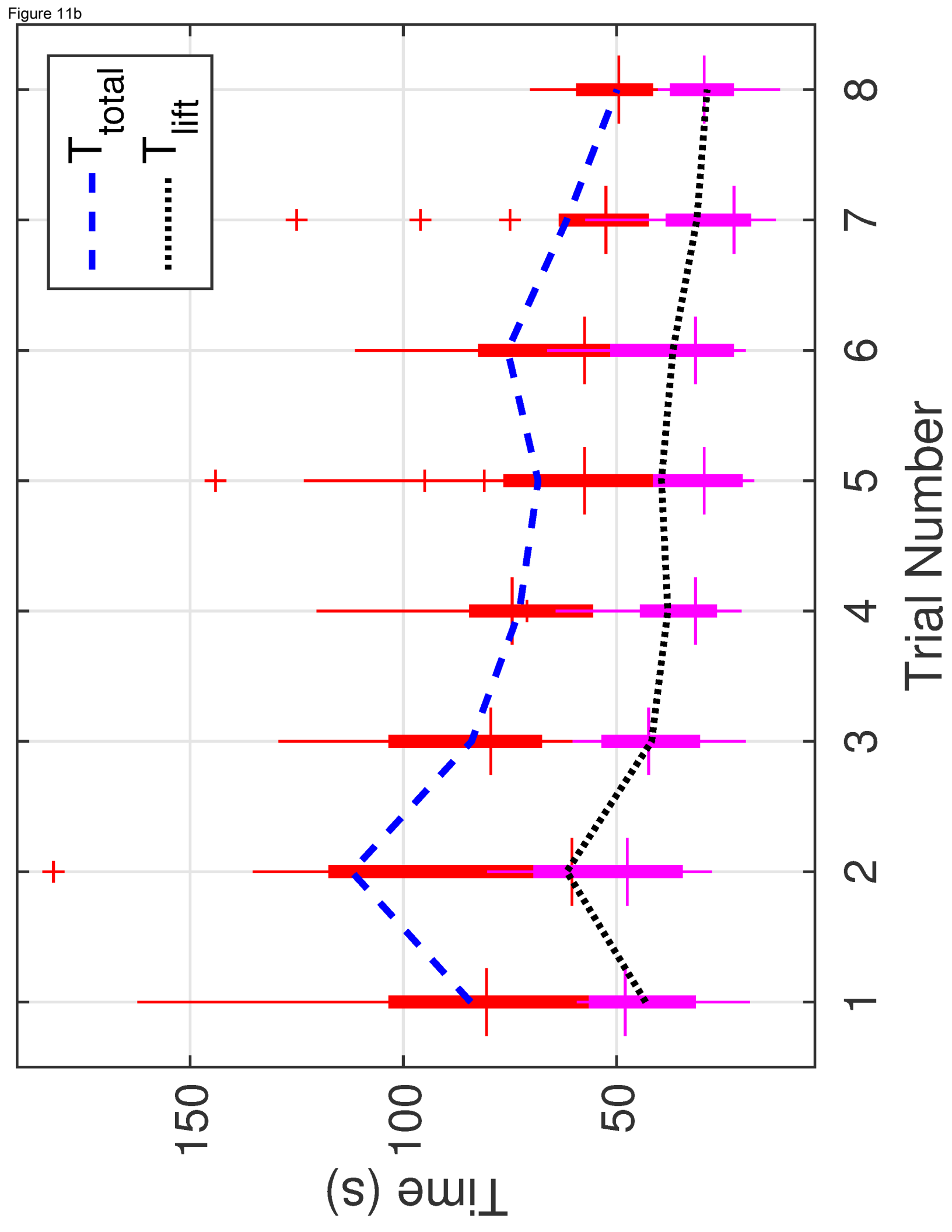
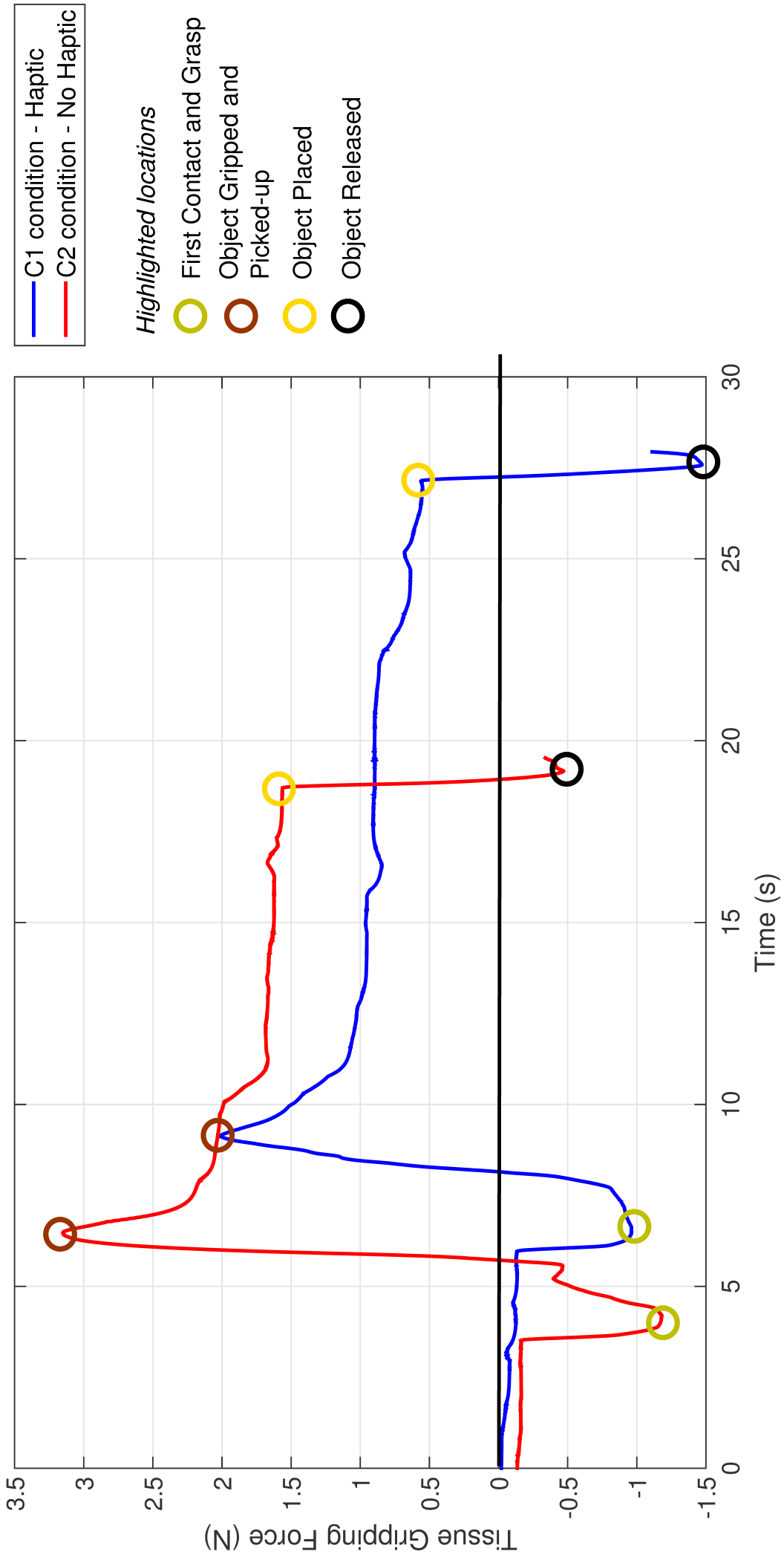


Figure 12a


C1 condition - Haptic
C2 condition - No Haptic
Highlighted locations
First Contact and Grasp
Object Gripped and Picked-up
Object Placed
Object Released
Tissue Gripping Force (N)
Time (s)
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
5
10
15
20
25
30

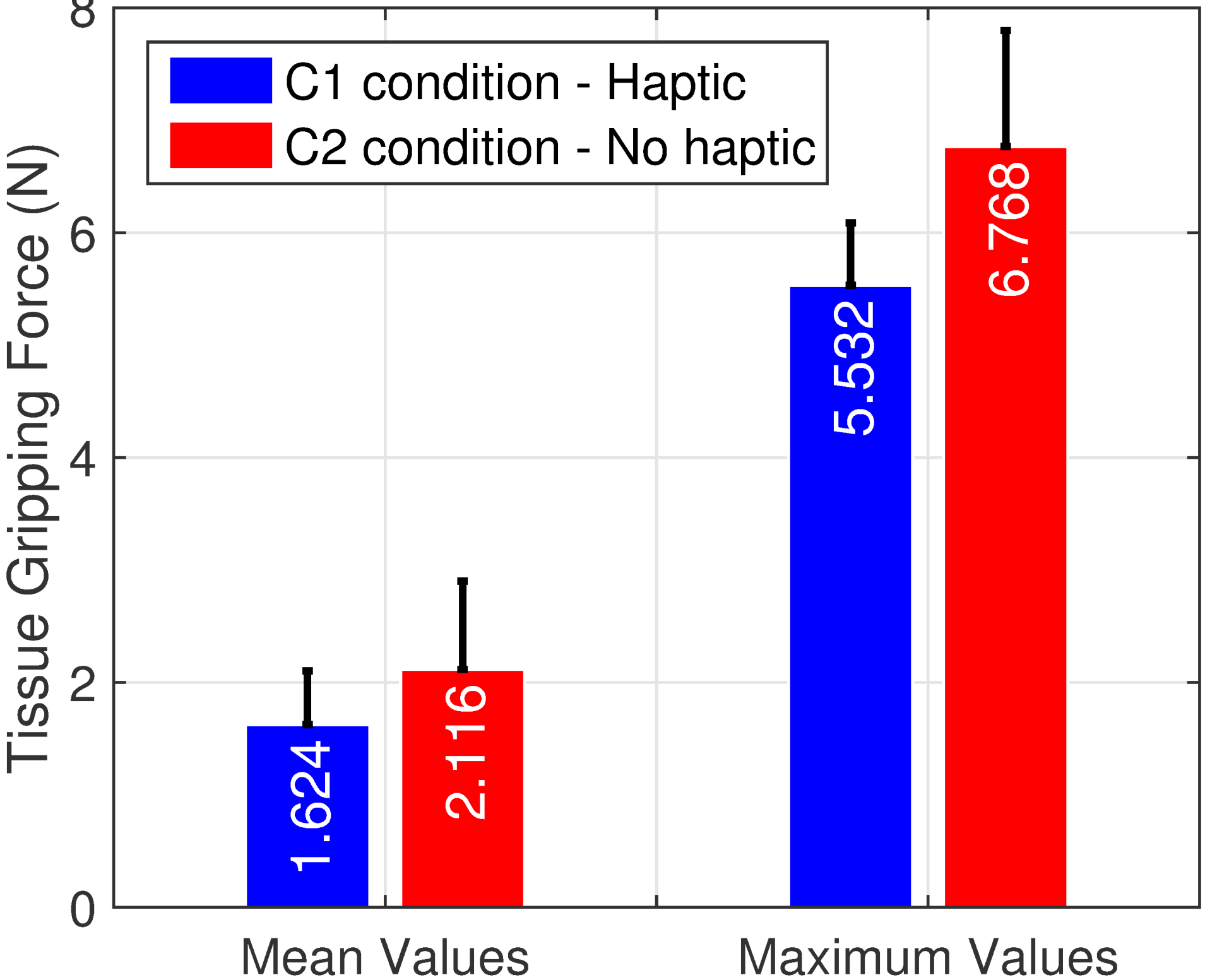

C1 condition - Haptic
C2 condition - No haptic
Tissue Gripping Force (N)
0
2
4
6
8
1.624
2.116
5.532
6.768
Mean Values
Maximum Values

Figure 12b

Figure 13

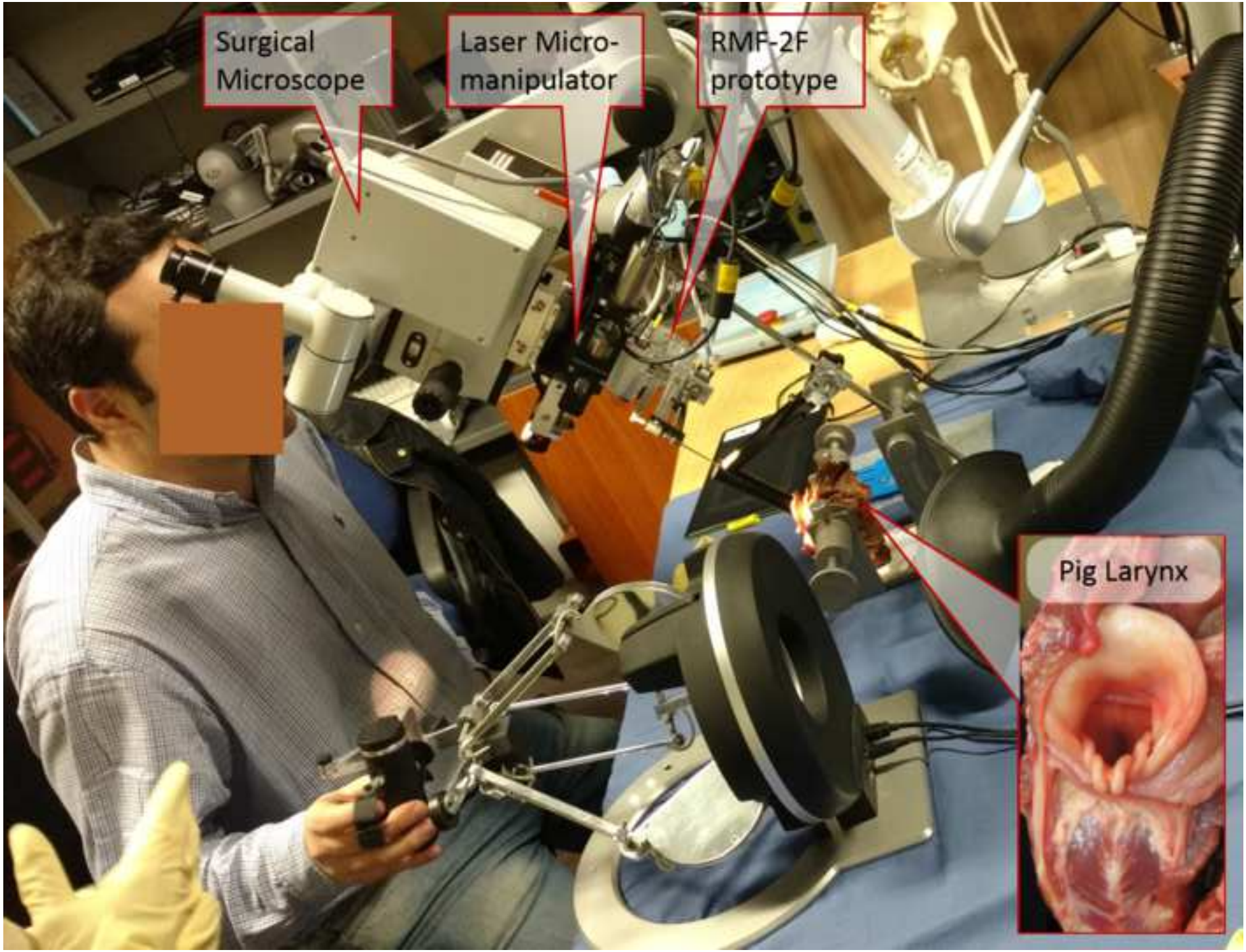

Surgical Microscope
Laser Micro-manipulator
RMF-2F prototype
Pig Larynx

TABLE 1: Design specifications of the microsurgical forceps

Design Needs / Features		Remarks
1.	Displacement from microscope line-of-sight of 200mm.	To minimize vision occlusion and avoid tool interference with laser path, sufficient distance between the laryngoscope entry point and the designed tool base is necessary.
2.	Tool cross-section under the microscope of <10mm.	To maintain minimum vision occlusion, when viewed through the microscope.
3.	Introduce tissue surface perception through haptic feedback.	To receive tissue gripping force feedback.
4.	Introduce tool rotation DOF.	Enhance tool capability for enhanced workspace and reachability.

Table 2

TABLE 2: D-H Parameters for the RMF-2F integrated device

Joint	Type	a (m)	α (radians)	d (m)	q (radians)
1	R	0.00000	$\pi/2$	d_1 = 0.089159	q_1
2	R	-0.42500	0.0	0.0000	q_2
3	R	-0.39225	0.0	0.0000	q_3
4	F	0.00000	$\pi/2$	d_4 = 0.10915	0
5	F	0.00000	$-\pi/2$	d_5 = 0.09465	0
6	F	0.00000	0.0	d_6 = 0.0823 + l_6	0
7	R	0.00000	$\pi/2$	d_7 = 0.108 + l_7	q_{rot}

R = Rotary; F = Fixed. l_6 = 210mm, l_7 = 200mm are dimensions of micro-forceps. q_{rot} = rotary DOF.