



Surgical assistant manipulator with diagonal joints and multi-stage telescopic screws for laparoscopic solo surgery

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Abstract

Purpose A surgeon in a sterilized area can perform robotically assisted laparoscopic solo surgery while controlling a laparoscope-holding robot for view stabilization and a forceps robot for pulling organs. At present, no locally operated surgical assistant manipulator with a mechanical remote center of motion (RCM) is available to operate within a small space while providing a wide range of movement. The present study describes a new locally operated detachable end-effector manipulator (LODEM) with diagonal joints and multi-stage telescopic screws.

Methods A forceps manipulator attached to commercial surgical forceps was developed. This manipulator uses RCM diagonal joints for the yaw and pitch axes, providing an intuitive pivot point and free rotation, and telescopic nested screws with multiple sliders clamp the commercial forceps for the axis of insertion. The manipulator placed above the abdominal wall using a fixed arm connected to a bed rail is motor controlled by a handheld interface with button switches for precise traction and is controlled manually for easy rough positioning.

Results Positional accuracy at the tip with a load of 5 N was under 0.5 mm. Mechanical deflection was under 2.1 mm. The manually controlled force was under 4.4 N. Successful simulated laparoscopic cholecystectomy using the prototype manipulator to handle the target and maintain stability was performed on a surgically realistic gallbladder model.

Conclusions A LODEM with diagonal joints and multi-stage telescopic screws was developed to facilitate minimally invasive, robotically assisted laparoscopic solo surgery by a surgeon working near the patient. This electric motor-controlled laparoscopic instrument holder by the surgeon in the surgical field could be used for such applications.

Keywords Surgical robot · Assistant manipulator · Remote center · Diagonal joint · Laparoscopic surgery · Local operation

Introduction

Background

Laparoscopic surgery producing only small scars has become widespread as a standard of care in developed countries [1]. Minimally invasive surgery offers substantial benefits to both

patients and doctors. Meanwhile, the need for surgery in low- and middle-income countries continues to rise [2]. In order to become a doctor, time and money are needed. In Malawi which is one of the least developed countries, the enrollment rate in higher education is low, and the financial cost of training a medical doctor is over US\$ 50,000 [3]. More training time and financial costs for making a surgeon are required after medical school education. The introduction of low-cost surgical assistant robots will give the time to grow up skilled surgeons. Robotically assisted laparoscopic surgery using locally operated assistant manipulators in a sterilized area represents one potential solution. By integrating surgical assistant robots, the surgeon can perform robotically assisted laparoscopic solo surgery while controlling a laparoscope-holding robot for view stabilization and a forceps robot for pulling organs. Solo surgery offers new opportunities for hospitals in reducing the numbers of surgeons present in the operating room (OR).

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Collaboration between the surgeon and surgical assistant robots during the surgery is important. The surgeon therefore needs to be provided intuitive pivot manipulation and a wide working area on the abdominal wall. Hence, the robot requires a suitable mechanical remote center of motion (RCM), should occupy a small space, and should be set up with the capacity for a wide range of movement.

State of the art

Tele-operated surgical robots with a camera arm and two or three tool arms [4], such as the da Vinci [5], IBIS [6], Senhance [7] (formerly known as ALF-X [8]), Versius [9], Avatera [10], and Hinotori [11], have been developed for a surgeon as a high-end tool to resolve problems such as limited degrees of freedom (DOFs), minimization of the effects of any hand tremors, and cooperation with assistants. Locally operated surgical assistant robots are intended to assist with the surgical workflow solely in laparoscopy. Laparoscope-holding assistant robots, such as the ViKY [12] (formerly known as LER [13]), FreeHand [14], EMARO [15], and SOLOASSIST II [16], have been developed for view stabilization [17]. Forceps assistant robots, such as the ANSUR [18] and the locally operated detachable end-effector manipulator (LODEM) with a commercial surgical forceps [19–24], have been developed for soft tissue retraction. These manipulators are categorized into three types, as follows.

Parallel link manipulators such as da Vinci [5], IBIS [6], and EMARO [15], and slider-crank or gimbal-mount LODEM [20, 24] with a mechanical RCM provide intuitive pivot manipulation, but the mechanisms occupy a large space above the abdominal wall and the range of movement is narrow when close to the horizontal position because of the linkages.

R-guided rail manipulators such as Viky [12] and FreeHand [14], and circular telescopic or ring-guided LODEM [21, 23] with a mechanical RCM provide intuitive pivot manipulation and a wide range of movement compared to parallel link manipulators, but the mechanism covers a large, hemispherical space on the abdominal wall.

Serial link manipulators such as Versius [9], Avatera [10], Hinotori [11] and SOLOASSIST II [16] with a motor-controlled RCM provide a wide range of movements, but the pivot manipulation is difficult to understand intuitively and the mechanism occupies a large space above the abdominal wall because of the thick arm. Cylindrical manipulators such as Senhance [7], ANSUR [18], and the SCARA LODEM [19] are also classified as serial link manipulators.

Purpose

At present, no locally operated surgical assistant manipulator offers a mechanical RCM that can operate within a small space while providing a wide range of movement on the abdominal wall. We therefore propose herein a new 3-DOFs forceps manipulator with diagonal joints and multi-stage telescopic screws attached to commercial surgical forceps for robotically assisted laparoscopic surgery performed by a single surgeon.

We have previously reported an overview of the proposed mechanism [25]. The present study describes the newly proposed manipulator with diagonal joints for mechanical RCM and a wide range of potential movements, and multi-stage telescopic screws for the small space. In addition, we report in detail the performance of the proposed manipulator in a simulated laparoscopic solo surgery.

Materials and methods

Concept of robotically assisted laparoscopic surgery with a forceps assistant manipulator

Figure 1 shows a conceptual diagram of robotically assisted laparoscopic surgery performed by a single surgeon. A laparoscope, forceps attached to an assistant manipulator, and two conventional tools operated by the surgeon hands are inserted into the abdomen through ports to remove a target organ, such as a gallbladder. The forceps assistant manipulator connected to a bed rail is placed above the abdominal wall. The manipulator has three DOFs (yaw, pitch, and insertion) and is controlled manually for easy rough positioning and is motor controlled for precise traction. The attached forceps, which have two DOFs (roll and grasp), are controlled manually to grasp the organ. The surgeon can perform robotically assisted laparoscopic surgery while controlling

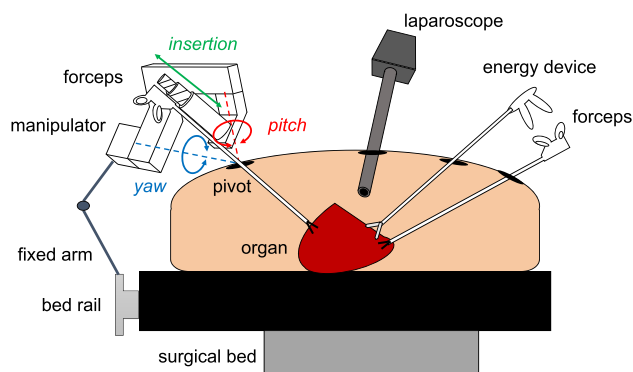


Fig. 1 Concept of robotically assisted laparoscopic surgery supported by a forceps assistant manipulator

the forceps robot for pulling organs continuously. The manipulator draped with a sterile cover can be removed from the surgical table as required.

Design and prototype

We propose a new 3-DOFs forceps manipulator with diagonal joints and telescopic multiple screws using multiple sliders attached to commercial surgical forceps. Figure 2a and b shows the mechanical design of the diagonal joints for the yaw and pitch axes, and telescopic multiple screws using multiple sliders for the insertion axis. The gap of 88 mm between the diagonal joints and the pivot is determined from the thickness of a commercial trocar head (50 mm). The yaw axis is set at a diagonal angle of 30° on the horizontal plane and the pitch axis is also set at a diagonal angle of 45°. The motor for the pitch axis is embedded in the diagonal arm using a bevel gear. RCM diagonal joints can produce free rotation to avoid collision with the mechanism for the insertion axis.

Figure 2c and d shows the details for the mechanical design of the insertion axis. The telescopic mechanism consists of three screws, three sliders, and a constant force spring. These three screws show a nested construction with screw 3 (length: 130 mm; outer diameter: 16 mm; inner diameter: M12; lead length: 1 mm), screw 2 (length: 130 mm; outer diameter: M12; lead length: 1 mm; inner diameter: M8; lead length: 1 mm), and screw 1 (length: 136 mm; outer diameter: M8; lead length: 1 mm). Three sliders connected to the nested screws are used for linear motion guides. The constant force spring (output force: 5.88 N, CR-5; Accurate, Koshigaya, Japan) is used for precompression in the short direction. The motor of the insertion axis is connected to screw 3 using a spur gear. Commercial surgical forceps (5 mm in diameter, ENDO CLINCH II; Medtronic, Dublin, Ireland) can be clamped using an attachment screw on the outer slider draped with the sterile cover. Manual control of the insertion axis is performed by rolling the motor-coupling part.

The manipulator is motor driven after manual positioning in the initial orientation. The operating range is - 90° to 30° for the yaw axis, -60° to 90° for the pitch axis, and 0 to 200 mm for the insertion axis as shown in Fig. 3a–c, decided on the basis of the pulling direction by the assistant’s forceps [26]. The requirements for the tip of the forceps are 5 N of applied force [27], velocity of 100 mm/s [28], and accuracy of 0.5 mm [20].

Figure 4a and b shows photographs of a prototype forceps manipulator. Each of the yaw and pitch axes is driven by a direct current (DC) servomotor (maximum continuous torque, 0.0304 Nm; efficiency, 0.88; maximum speed, 9690 rpm; RE25 339,152; Maxon Motor, Sachseln, Switzerland) with a planetary gear head (gear ratio: 139, efficiency: 0.70, GP26A406770; Maxon Motor) and an encoder (reso-

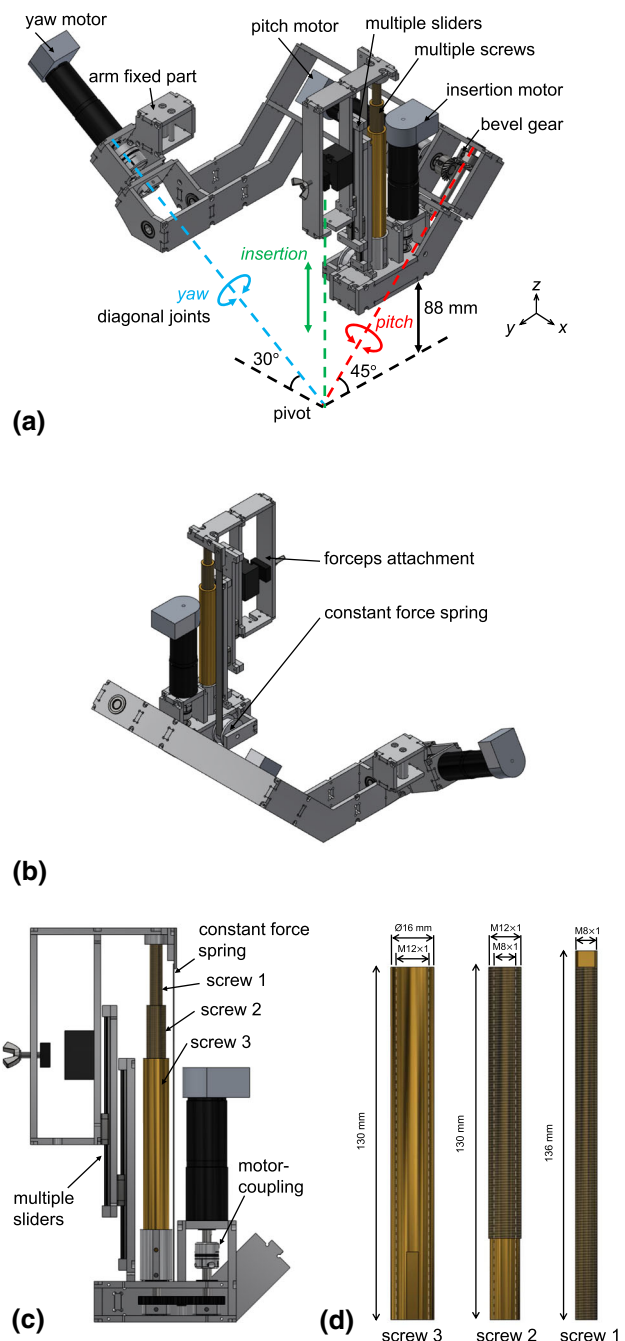


Fig. 2 Mechanical design of the forceps manipulator with diagonal joints for the yaw and pitch axes, and multi-stage telescopic screws for the insertion axis: **a** front perspective view; **b** side perspective view; **c** telescopic mechanism using three screws and three sliders; and **d** nested construction with screws

lution: 500 pulse; HEDL5540 110,512; Maxon Motor). The insertion axis is driven by the same DC motor with a planetary gear (gear ratio: 27; GP 26A406764; Maxon Motor) and the same encoder. The main materials are duralumin for the diagonal arm, brass for the telescopic screws, and stainless steel for gears and sliders. The dimensions of the manipu-

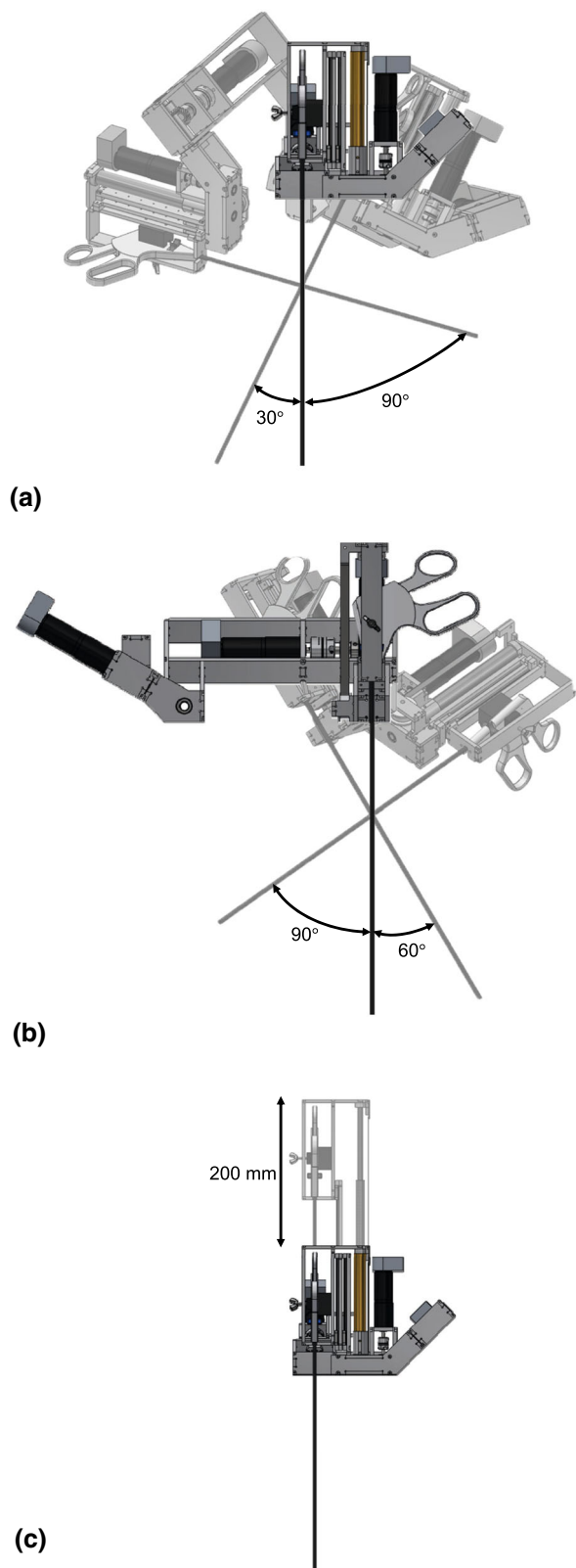
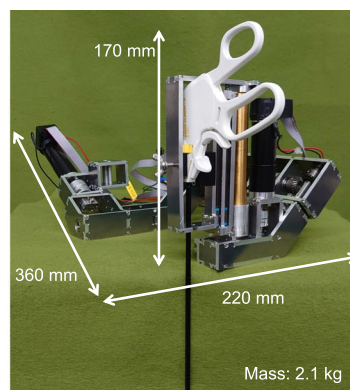
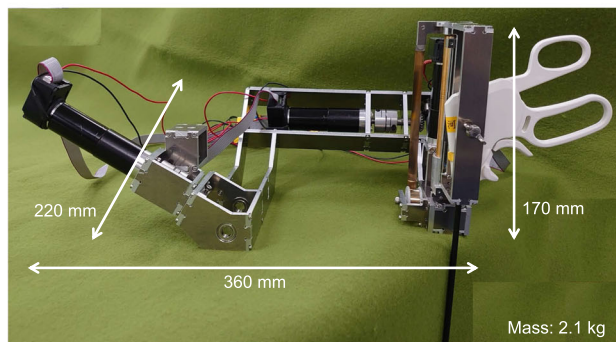


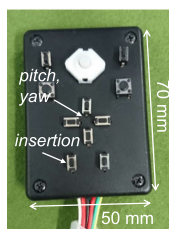
Fig. 3 Operating ranges of the forceps manipulator: **a** yaw axis; **b** pitch axis; and **c** insertion axis



(a)



(b)



(c)

Fig. 4 Prototype of the forceps manipulator: **a** front perspective view; **b** side view; and **c** handheld interface with button switches

lator are 360 mm × 220 mm × 170 mm. The mass is 2.1 kg. The manipulator is motor controlled by a handheld interface (70 mm × 50 mm; 35 g) with button switches as shown in Fig. 4c. Commands to control the individual axes are input by pressing the appropriate buttons, and these commands are processed by a positioning controller (EPOS2 24/2 DCX, 530,239; Maxon Motor), which then outputs the appropriate signals to the manipulator.

Experimental methods

To evaluate the new manipulator, the prototype was used in the experiments as described below. Experiments 1 and 2 were performed to confirm positional accuracy of the motion trajectory and the manually controlled force. Experiment 3

was designed to confirm the feasibility of using the manipulator as a surgeon's assistant in simulated laparoscopic surgery.

1. Independent motion trajectories of the prototype with a stainless steel rod (outer diameter: 5 mm; length: 300 mm; weight: 50 g) as the surgical tool for the three axes when loaded by 0 N and 5 N at the tip of the bar were measured using an optical displacement sensor (accuracy: 0.1 mm; OPTOTRAK Certus; NDI, Waterloo, Canada). The length from the pivot to the tip of the bar was 200 mm. The sensor marker measuring the trajectory was attached to the mechanism where the length from the pivot was 218 mm. In these experiments, positional accuracy at the tip of the bar was defined as the maximum difference in hysteresis under a load of 5 N. Mechanical deflection was defined as the maximum difference in motion trajectory between 0 N and under a load of 5 N.
2. The independent, manually controlled force of the unpowered prototype with the stainless steel rod for the three axes was measured using a force gauge (resolution: 0.01 N; ZP-50 N; IMADA, Toyohashi, Japan). Length from the pivot to the tip of the bar was 200 mm. The measuring point was at the tip of the bar in an orthogonal direction for the yaw and pitch axes, and at the motor coupling (outer diameter: 14 mm) in the tangential direction for the insertion axis. Manually controlled force was defined as the averaged static force at the initiation of movement in five trials.
3. Simulated laparoscopic cholecystectomy was performed on a surgically realistic gallbladder model (50,128; Limbs and Things, Bristol, UK) in a training box (Endowork-pro II; KARL STORZ, Tuttlingen, German) by a specialist. A laparoscope (diameter: 10 mm; Tricam 3D; KARL STORZ) was positioned on the foot side of the surgical table using an autoclavable fixed arm (OCT-03L; Yufu Itonaga, Osaka, Japan) connected to the bed rail. Forceps attached to the manipulator were positioned on the left-hand side of the table using an autoclavable fixed arm (Snowden Pencer Fast Clamp System; CareFusion 2200, San Diego, CA) connected to the bed rail. The operator, a laparoscope specialist, stood at the foot side of the table and used scissors in his right hand and forceps in the left hand. The manipulator was controlled by a handheld interface with button switches. The experimental setup is shown in Fig. 5.

In clinical laparoscopic cholecystectomy, the surgeon dissects the gallbladder using scissors or an electric scalpel under sufficient tension produced by his forceps and the assistant's forceps. The assistant is needed to keep the lower edge of the liver elevated to allow a perfect view on the gallbladder. The role of the proposed forceps manipulator as the assistant

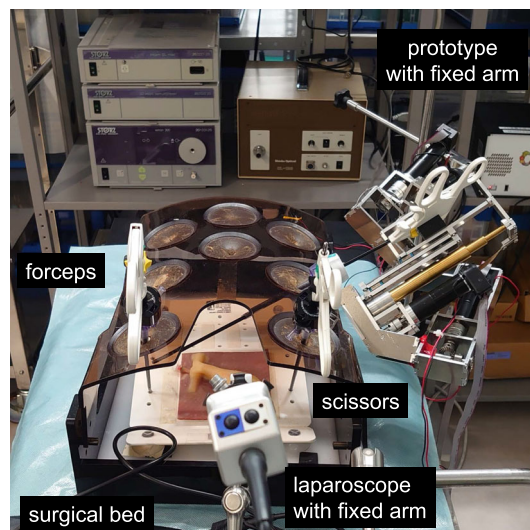


Fig. 5 Experimental setup for simulated laparoscopic cholecystectomy using the prototype forceps manipulator

in the simulated surgery was determined to pull up and hold the organ model continuously during dissection. The simulated surgery was started at grasping the organ and ended at completing the dissection. Manual control time, on/off switch control time, and holding the organ time using the prototype forceps manipulator were measured using a video camera filming of a laparoscopic monitor, the experimental setup on the surgical bed, and the laparoscope specialist. This physician had experience using some forceps assistant manipulators with different mechanisms although the controllers of button switches were similar in shape [20, 21, 23, 24]. The specialist had training with the new manipulator before the experiment for a few minutes. The on/off switch controller and the gallbladder model were familiar to the surgeon, however, the manual control and the motor control for the proposed manipulator were the first time in the simulated surgery.

Results

Results of the three experiments were as follows.

1. Figure 6 presents the results of trajectory measurements in the moving direction under loads of 0 N and 5 N. Positional accuracy at the tip of the bar was 0.5 mm for the yaw axis (Fig. 6a), 0.4 mm for the pitch axis (Fig. 6b), and 0.4 mm for the insertion axis (Fig. 6c). Mechanical deflection was 2.1 mm for the yaw axis, 1.1 mm for the pitch axis, and 0.5 mm for the insertion axis.
2. Manually controlled force at the tip of the bar was 4.3 N for the yaw axis, 1.8 N for the pitch axis, and 4.4 N for the insertion axis.

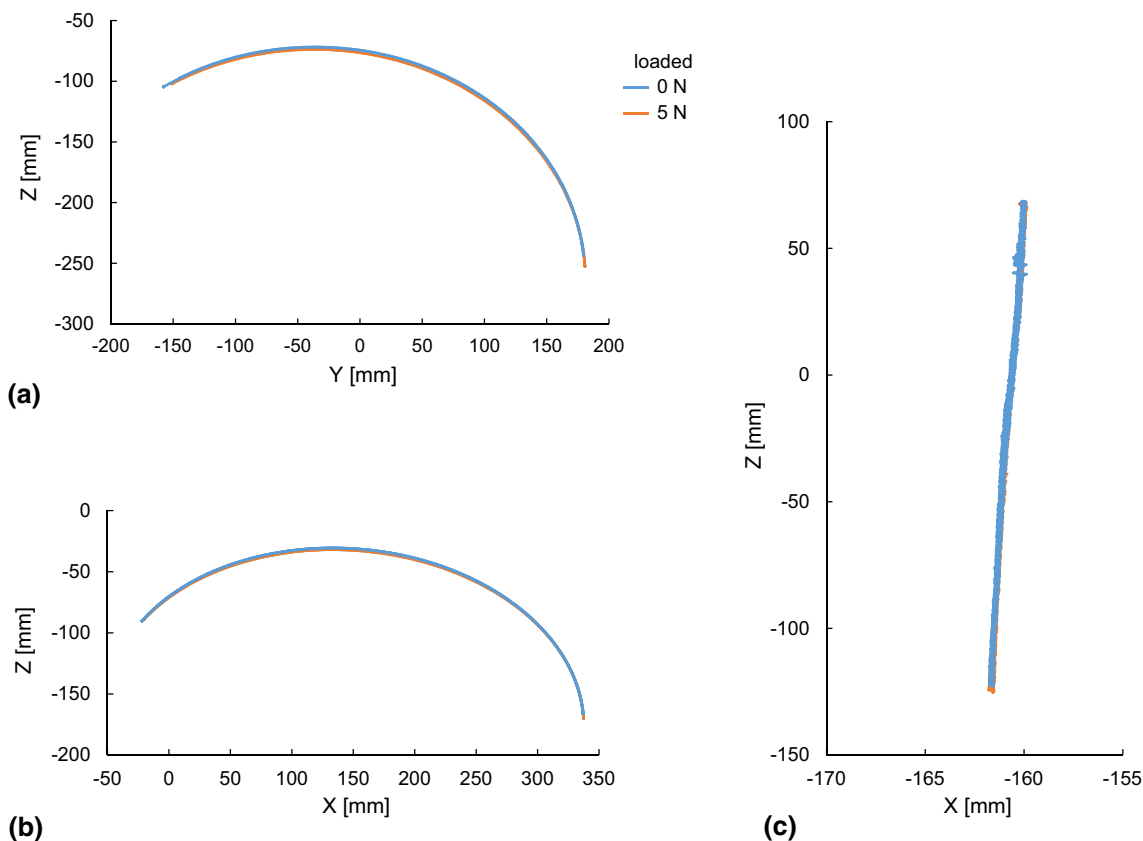


Fig. 6 Results of trajectory measurements of the forceps attachment in the direction of movement when loaded by 0 N or 5 N: **a** yaw axis; **b** pitch axis; and **c** insertion axis

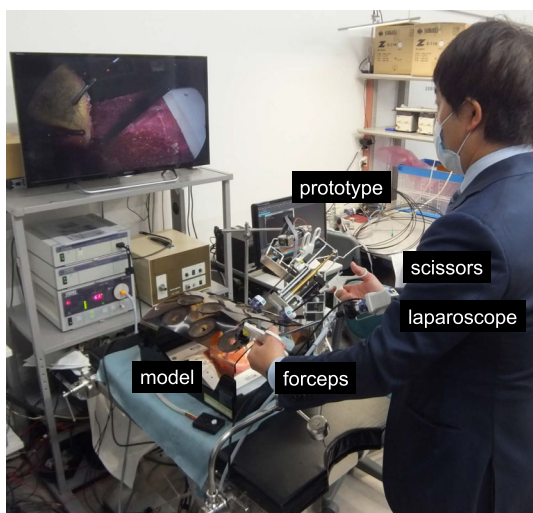


Fig. 7 Simulated laparoscopic cholecystectomy performed on a surgically realistic gallbladder model in a training box by a laparoscope specialist using the prototype forceps manipulator

3. Figure 7 shows a photograph of the simulated laparoscopic cholecystectomy. Manipulator angle was changed manually to grasp and pull the gallbladder model so as

to perform the simulated laparoscopic cholecystectomy. The forceps manipulator was then driven by the motors under the control of the surgeon and retracted the organ model continuously. The organ model could be pulled in various desired directions using the forceps attached to the manipulator. The forceps held in the left hand could also be used to grasp and pull the model organ in the opposite direction with sufficient tension, while the scissors held in the right hand could be used to dissect the organ model. Smooth dissection of the organ model was performed by the laparoscope specialist at sight. Successful simulated laparoscopic surgery was performed for 15 min 30 s, as shown in Fig. 8. Detailed durations were 1 min 9 s for manual control, 4 min 4 s for the on/off switch control, 9 min 23 s for holding organs in operations using the surgeon's hands, and 54 s for forceps replacement. Even though accidental forceps replacement was occurred, a few manual controls to change the operative field, and a dozen of on/off switch controls to maintain the tension for the organ model were performed.

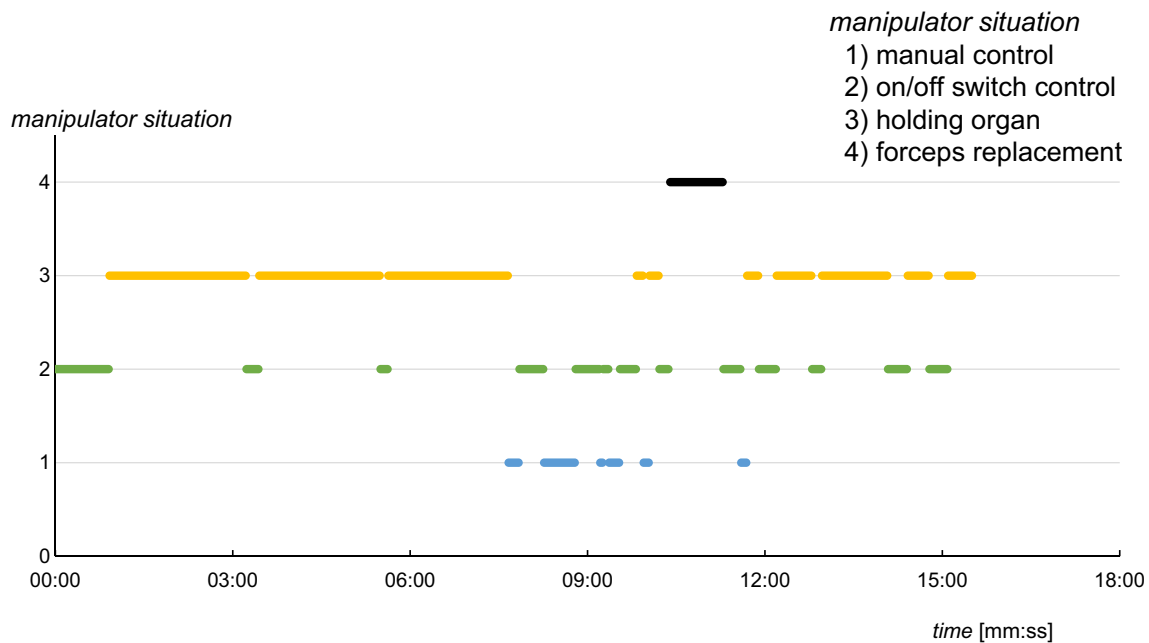


Fig. 8 Results of time measurements for simulated laparoscopic cholecystectomy by the laparoscope specialist using the forceps manipulator prototype in situations categorized as 1–4: **1** manual control; **2** on/off switch control; **3** holding organ; and **4** forceps attachment

Discussion

The forceps manipulator with diagonal joints and multi-stage telescopic screws was developed to keep the mechanical RCM within a small space while providing a wide range of movement. The diagonal joints in the pitch and yaw axes can produce a mechanical pivot point on the abdominal wall for intuitive manipulation similar to parallel linkage [5, 6, 15] and R-guided rail [12, 14] manipulators and can also produce a wide range of movement comparable to that with serial link manipulators [7, 9, 11, 16, 18] in principle when the arm does not collide with the insertion axis. The multi-stage telescopic screws of the insertion axis occupy a small space when shortened.

The direct rotational pitch axis, the bevel-gear rotational yaw axis, and the screwed linear insertion axis lead to the required positional accuracy because of a few air gaps and backlash. The multiple sliders and constant-force spring of the insertion axis lead to suppression of mechanical deflection because of the closed loop mechanism and pre-compression. Mechanical deflection for the yaw and pitch axes of the diagonal joints can be reduced once processing and assembly accuracy are improved.

Positional accuracy under 0.5 mm and manually controlled force under 5 N contributed to precise traction and easy rough positioning for target organ as the surgical assistant in the simulated surgery. The new forceps assistant manipulator could be used by the laparoscope specialist to successfully handle the target organ model. The intuitive

pivot manipulation, wide working area on the abdominal wall, and quick and accurate provision of the required surgical scenes for the surgeon were confirmed in a dry laboratory environment. Robotically assisted laparoscopic solo surgery produced by a doctor working near the patient while controlling the forceps manipulator was also confirmed. According to comparison of different laparoscope robots in a gallbladder phantom model [29], dissection time using early robots such as AESOP and FIPS was between 13 and 18 min, while a control group involving an assistant surgeon was 16 min. Although a simple comparison is not accurate, the simulated surgery for 15 min in this study equal to the result using the former gimbal-mount LODEM [24] indicates that the proposed forceps manipulator could be pulling and holding the gallbladder continuously as the assistant.

The pitch and yaw axes of the manipulator are not perpendicular. The perpendicular gimbal coordinate is more intuitive in general, but the specialist could smoothly control the manipulator with oblique coordination. The reason for this smooth control is that the surgeon estimates the pulling force and direction from the surface of the organ in the laparoscope monitor. A forceps assistant manipulator is important to facilitate collaboration with the surgeon during robotically assisted surgery.

The interface for controlling the manipulator is important. The proposed manipulator for the present system is controlled by a handheld button switch. Laparoscope assistant manipulators can be controlled by interfaces such as handheld switches [16], head-mounted sensors [14, 15], and

vocal commands [12]. In the meantime, tele-operated surgical robots represent a master-follower system. Movement of the master device is similar to that in conventional open or laparoscopic surgery, so the surgeon can operate intuitively. A hybrid controller with easy on/off switching and intuitive master-follower movement appears suitable for the assistant manipulator. A master-follower selectable control system enables control devices to be exchanged easily [30].

Many types of laparoscope or forceps fixed arms, such as mechanical type using experiments in this study, pneumatic type [31], hydraulic type, and spring type [32] have been developed. The passive instrument holder requires handling and fixation repeatedly when the tension of organs come loose, for example elevating the gall bladder. The surgeon is difficult to concentrate the laparoscopic monitor while controlling the passive holder manually on the surgical bed, whereas the surgeon can perform pulling organs with focusing the monitor while controlling the proposed motor driven active holder. However, additional electronic devices in OR lead to more electric wiring and maintenance time for surgical operations.

Solo three-incision laparoscopic cholecystectomy using the laparoscope holder is performed to overcome an inexperienced scopist or a shortage of skilled manpower [33]. The solo laparoscopic surgery using active holders with the laparoscope and the forceps could be used for other surgical procedures. Expansion into other surgeries using the proposed forceps manipulator is under consideration. The proposed system has a potential to be used for benign diseases, such as appendectomy, inguinal hernia repair, uterine myomectomy, or nephrectomy. For operations in humans, downsize mechanism made of stainless material and attachments applied to commercial forceps are needed. Furthermore, two or more assistant manipulators are used for complex procedures. As to the installation of the robot with light weight separately, connection to the surgical bed rail is suitable [9, 12, 14, 16]. The easy fixed arm for the assistant robot is needed. Future work includes also improvements of simulated surgery. The experimental environment using a surgical gallbladder model in this study is limited. The use of a liver model covering the gallbladder model is one of the improvement simulated surgery to produce holding the liver up to create tension for the dissection from above.

Tele-operated robotic surgical systems have high fixed costs, with prices ranging from US\$ 1 million to US\$ 2.5 million [34]. Laparoscope-holding assistant robots have relatively low costs, with prices about US\$ 100,000 [35]. Further simple structured assistant robot leads to lower cost and the robotic assisted solo surgery using assistant robots would be feasible for low- and middle-income countries.

Conclusions

We developed a 3-DOFs forceps manipulator with diagonal joints and multi-stage telescopic screws attached to commercial surgical forceps for laparoscopic surgery performed by a single surgeon. The mechanism of diagonal joints and multi-stage telescopic screws, providing the mechanical RCM within a small space while offering a wide range of movement, was designed to facilitate minimally invasive, robotically assisted laparoscopic solo surgery by a doctor working near the patient. The present results indicate that the proposed manipulator may be feasible for use in such applications.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11548-021-02553-4>.

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Declarations

Conflict of interest The authors declare that there are no conflicts of interest with regard to this study.

Ethical approval This article does not describe any studies with human or animal subjects.

Informed consent This article does not contain patient data.

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