A Novel Handheld Bimanual Surgical Robot for Single-Port Laparoscopic Surgery

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Research

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A novel handheld bimanual surgical robot for single-port laparoscopic surgery

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Abstract

Background: single-port laparoscopic surgery is a hotspot of minimally invasive surgery, but its promotion is limited because of operational triangulation and instrument conflict. Robot technologies can cleverly solve this dilemma. But most of the surgery robots need high cost and long time to setup and mainly for complex surgery currently. There is no portable single-port laparoscopic robotic surgical instruments suitable for simple abdominal surgery.

Result: This paper presents a handheld single-port laparoscopic surgical robot. It consists of two manipulate arms, both of the arms have 2 degrees of freedom, and two more degrees of freedom can be applied by handheld. The left arm has the function of pulling tissue, while the right arm is equipped with a laser fiber, which can be used for tissue cutting and hemostasis with a 980nm diode laser. Kinematics analysis, dynamic simulation, modal analysis and vitro simulation experiments were conducted to verify the feasibility for the handheld single-port laparoscopic robot.The bimanual surgical robot can provide enough workspace, the gripper and laser head have stable working ability, and can successfully complete the fenestration and drainage of hepatic cyst.

Conclusion: This bimanual surgical robot has the potential to become a surgical instrument for simple intraperitoneal surgery. It can provide a small, portable and inexpensive surgical robot system.

Keywords：single-port laparoscopic surgery; bimanual surgical robot; kinematic analysis; hepatic cyst

Background:

Laparoscopic surgery, also called minimally invasive surgery (MIS). Laparoscopic surgery not only meets the needs of patients in terms of cosmesis but also can reduce postoperative pain and intestinal obstruction time, so that patients can recover faster, stay in hospital for a shorter time, and return to normal activities earlier(1-5). But most laparoscopic procedures usually requires 3-6 small incisions for ports. Given the development of laparoscopic technique, single-port laparoscopic surgery (SPLS) become a new tendency(6-10). SPLS is more difficulty for surgeon to learn and manipulate because surgical instruments frequently encounter motion limitations and clashing due to crowding. The most important thing is that SPLS significantly increases the difficulty of operative site exposure and dissection due to inability of triangular dissection which has been considered a cornerstone of laparoscopic surgery.

So, there are some measures to overcome those limitations, including inverse triangulation, pivoting, spreading out dissection, hanging suture, transluminal traction(11). But these measures either change the surgeon's habit or increase the operations step and often results in awkward hand movements in which the surgeon's hands control the opposite end effectors. Furthermore, robot-assisted technology is a new technology to solve that problem(12). Most of these limitations during multiport laparoscopic surgery have been solved with the aid of robotic technology.

Robot-assisted technology has increased the distribution of laparoscopic surgery and revolutionized the way of surgery. Surgeons and research teams have developed several types of single-port laparoscopic robots , including Da Vinci SP(13) ,

SPIDER(14), QuadPort(15),etc. The parallel use of robotic surgery with single-port platforms, however, appears to counteract technical issues associated with single incision laparoscopic surgery through significant ergonomic improvements, including enhanced instrument triangulation, organ retraction, and camera localization within the surgical field. Robot-assisted single-port laparoscopic surgery system have been used in radical prostatectomies(13, 16), cystectomy(17), mediastinal mass(18), laryngo-pharyngeal cancer(19), head and neck surgery(20). However, most of those are complicated surgery, and these robot-assisted single-port laparoscopic surgery are bulky and have a long learning curve. Besides, the mean time of setup and takedown for Da Vinci is more than 1 hour and laparoscopic surgery is more cost effective than it in cost analysis with an economic model(21), The longer of the setup and takedown, the longer the patient will have to undergo general anesthesia. those disadvantages making them difficult to promote in primary hospitals. So, the current RASPLS is not apply to everyone who needs surgery, especially the poor and the surgery is less complicated.

Hepatic cyst is a common benign disease of the liver. Some patients with the increasing of cyst or oppression surrounding tissue can appear some symptoms, including abdominal pain, bloating, liver enlargement, abdominal mass, nausea, vomiting, and loss of appetite. More serious can appear ascites, edema, jaundice, hemorrhagic hepatic cyst and other symptoms(22-24). Today, laparoscopic with two or three ports has been widely used in fenestration and drainage of hepatic cyst(24). We should also pursue a single port laparoscopic to this procedure. But, using the da Vinci®

Surgical System is too expensive to extended to everyone.

So, we need portable surgery robots that cheap and easy to setup and operate. In this paper, wo present a microsurgical robot for laparoscopic surgery. The device that mounted a 980-nm diode laser(25) on the right arm for incising can be used to operate fenestration and drainage of hepatic cyst under a magnetically anchored camera(26), The feasibility of the equipment was verified through kinematics analysis, dynamic simulation and simulated vitro experiment.

Result:

1. Kinematic analysis

The bimanual robot consists of a left arm and a right arm. Both arms have the same range of motion of joints, internal structure and size, so as long as we conduct the kinematic analysis on either of them, we can obtain the kinematic characteristics of the other.

1.1 Establishment of connecting rod and connecting rod coordinate system

The bimanual robot has four degrees of freedom, namely three degrees of rotation and one degree of movement. In this paper, D-H method is adopted to establish the coordinate system of each link of the robot, as shown in Fig 1. The relationship between adjacent links is represented by four parameters (Table 1), θ -joint Angle, d- link offset, a-link length and α -twist Angle. The two degrees of freedom, θ_1 and d, are generated by the hand. Other two DOF , θ_2 and θ_3, are generated by the robot itself.

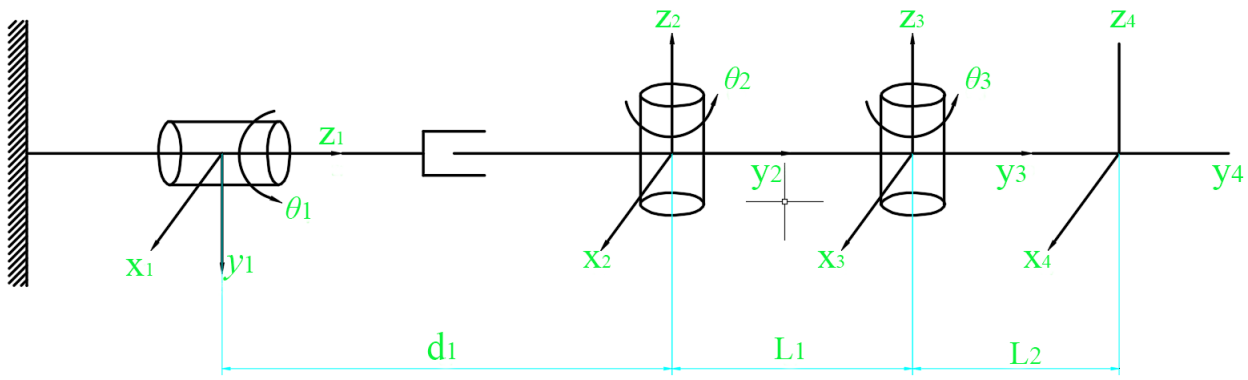


Fig.1 Coordinate system of each link of the robot

Table 1. Connecting rod parameters and joint variables of left arm of the bimanual robot

adjacent links	Joint rotation angle, θ i(°)	Twist angle, α i-1(°)	Distance di, (mm)	Rod length, a (mm)	Range of rotation angle, (°)
1	θ 1（0）	0	d1 (0~30)	0	0~-360°
2	θ 2（0）	0	0	35	-45° ~45°
3	θ 3（0）	0	0	50	-45° ~45°

With D-H method, use a 4x4 homogeneous transformation matrix to describe the spatial relationship between two connecting rods, and allow the coordinate system {i} to be coincident with the coordinate system {i-1} through rotation and translation. Therefore, the coordinate transformation matrix of the coordinate system {i} in the coordinate system {i-1} is:

$$ {}^{i-1}_{i}T = Rot(x,\alpha_i)Trans(a_{i-1},0,0)Rot(z,\theta_i)Trans(0,0,d_i) $$

According to the above method and the relevant data in Table 1, it is possible to establish the equivalent homogeneous transformation matrix of the coordinate system of the end tool (grippers or laser head) relative to the base coordinate system in turn, so as to establish the kinematic equation of the bimanual robot. The orientation matrix of the execution end in the base coordinate system is（*q1 represents* θ_1 *and so on*）:

$$ T1 = \begin{bmatrix} -\sin(q1), & -\cos(q1), & 0, & 0 \\ \cos(q1), & -\sin(q1), & 0, & 0 \\ 0, & 0, & 0, & d1 \\ 0, & 0, & 0, & 1 \end{bmatrix} $$

$$ T2 = \begin{bmatrix} \cos(q2), & -\sin(q2), & 0, & -L1 * \sin(q2) \\ \sin(q2), & \cos(q2), & 0, & L1 * \cos(q2) \\ 0, & 0, & 1, & 0 \\ 0, & 0, & 0, & 1 \end{bmatrix} $$

$$ T3 = \begin{bmatrix} \cos(q3), & -\sin(q3), & 0, & -L2 * \sin(q3) \\ \sin(q3), & \cos(q3), & 0, & L2 * \cos(q3) \\ 0, & 0, & 1, & 0 \\ 0, & 0, & 0, & 1 \end{bmatrix} $$

$$ T = T1 * T2 * T3 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$\vec{n}, \vec{o}, \vec{a}, \vec{p}$ are normal vector, direction vector, approach vector and position vector of the execution end, respectively. The coordinate system of the execution end is in the same direction as the base coordinate system.

1.2 Simulation analysis of the workspace

Based on the position and attitude of the coordinate system of the end actuator and the rotation range of each joint, simulate the workspace by programming in MATLAB

with Monte Carlo method, and obtain the 3D point cloud diagram of the whole space. The workspaces of the robot is shown in Fig 2.

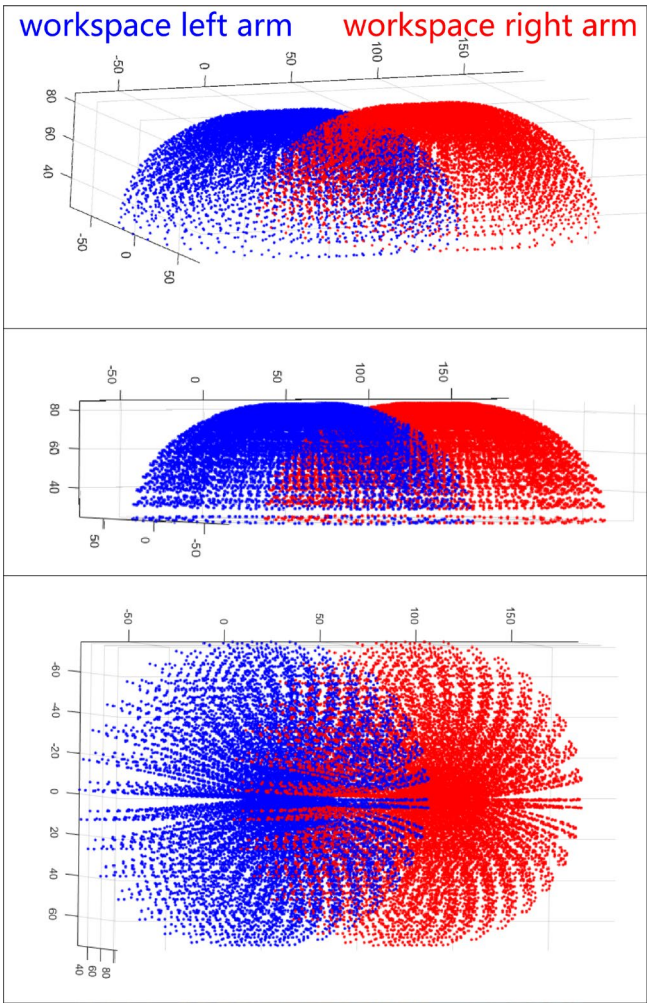


Fig.2 The workspaces of the bimanual robot

2. Dynamic simulation analysis

The gripper is mainly used to drive the slide by the motor to make a linear motion in the shell, which is finally converted into the stripping action of the actuator end of the rod-mechanism. Obtain the stripping force of the stripper through dynamic simulation analysis, as well as the speed and acceleration curve of the working process.

The highest torque of the motor is 900g·cm(88.2N.mm). In the operation, the motor is connected with the slide through inside sleeve with threaded. Parameters are as follows: thread median diameter d=7.51mm, lead of thread S=1mm, thread angle α=30°. The thrust F generated by the slide is expressed with the following equation: $F = \frac{2T}{d \times tan(\gamma + \rho_v)}$, Where, γ -guide stroke angle,$\gamma = arctan\frac{S}{\pi d}$; ρ_v-equivalent friction angle, $\rho_v = arctan\frac{u}{cos\frac{\alpha}{2}}$; u -friction coefficient, find it to be 0.08 by looking up the table. Obtain the thrust generated by the slider by substituting the above parameters into the equation, $F = 175N$.

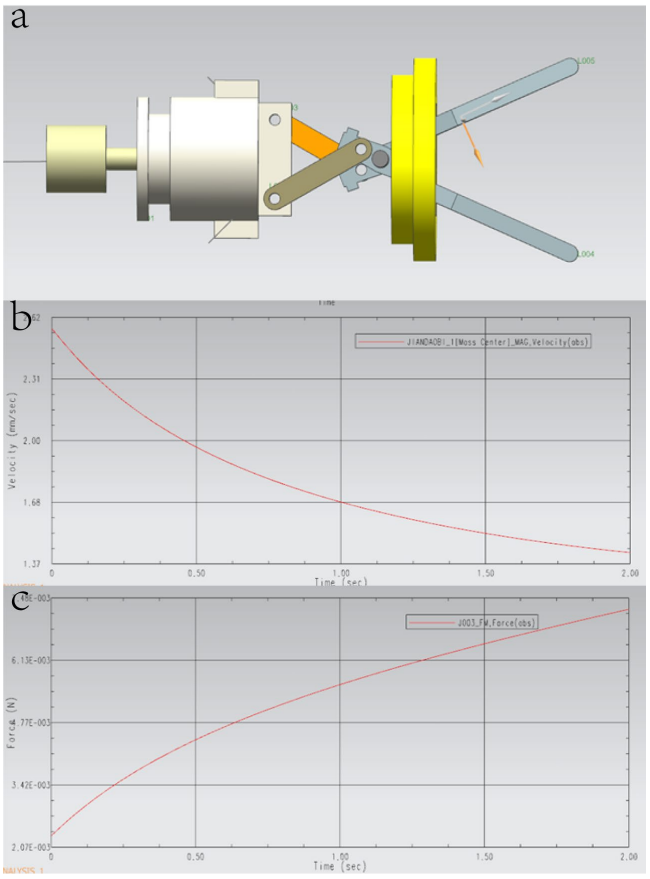


Fig.3 kinematic simulation analysis

Based on the above calculation results, import the model into the UG simulation module (Fig.3), and establish the dynamic simulation model of the

stripper (Fig.3a). the speed and force of gripper changing smoothly in dynamic simulation (Fig.3b, c).

3. Modal analysis

Upon operation of the bimanual robot, the parts will inevitably produce forced vibration under the action of periodic load. Especially when the excitation frequency of the exciting force is equal to or close to the natural frequency of the parts, the resonance of the structure will occur, resulting in strong vibration noise and structural damage. Modal analysis can evaluate the natural vibration characteristics of mechanical structures. The finite element analysis (FEA) method is a numerical calculation method used to solve various engineering problems. For a continuous system with an actual elastic structure, the kinetic balance equation of the discrete system with n-DOF can be obtained by discretizing it with the FEA, and the finite element calculation equation of the system is:

$$[M]\ddot{u} + [C]\dot{u} + [K]u = [F] \qquad (1)$$

Where, $[M]$ is the mass matrix, $[C]$为 is the damping matrix, $[K]$ is the rigidity matrix, $\ddot{u}$ is the acceleration vector, $\ddot{u}$ is the acceleration vector, u is the displacement vector, and $[F]$ is the external load matrix.

Static analysis refers to analyzing the stress distribution and strain of the structure under the static load. Upon analysis, the quantities related to time t are ignored. So Equation (1) is simplified as:

$$[K]u = [F] \qquad (2)$$

The model of relevant parts of the bimanual robot is the undamped multi-DOF linear vibration system, with its kinematic equation as follows:

$$[M]\ddot{u} + [K]u = [0] \quad (3)$$

The undamped modal analysis model is a typical eigenvalue problem with its solution form as follows:

$$u = u_i \, sin(\omega_i t) \quad (i = 1,2 \cdots n) \quad (4)$$

By substituting Equation (4) into Equation (3), obtain:

$$([K] - \omega_i^2[M])u_i = [0] \quad (5)$$

The eigenvalue of Equation (5) is ω_i^2, ω_i is the frequency of the system vibration circle, and the eigenvector u_i corresponding to ω_i is the mode of vibration corresponding to the natural vibration frequency $f = \frac{\omega_i}{2\pi}$.

The structure of the left arm is basically the same as that of the right one, and the stability of the laser head is very important during operation because laser head will result in inaccurate positioning due to structural resonance. So, modal analysis of the left arm of bimanual robot and the laser head is carried out in this paper. The results of the right one can be referenced from those of the left bimanual robot. The first six-order modal frequency and the first three-order mode of vibration of each part are obtained.

For the ease of calculation, it is assumed that each joint position is fixed through is rigid connection. See Table 2 for the first six-order modal frequencies of the left arm. The resonance frequencies of left arm of bimanual robot range from 65.01 Hz to 412.62Hz. The modal analysis of the laser head is carried out. The first six-order modes

of vibration are shown in Table 2. The resonance frequencies of laser head of bimanual robot range from 2851.2 Hz to 15249Hz.

Table.2 the first six-order modal frequencies of the bimanual robot

Component	one	two	three	four	five	six
Left arm(Hz)	65.01	71.58	136.89	140.68	366.19	412.62
Laser head(Hz)	2851.2	3104.2	8200.8	8448.1	11137	15249

In order to represent the vibration characteristics of the left bimanual robot at a certain working position in an intuitive manner, select the first three-order modes of vibration of the left arm for calculation, as shown in Fig 4. The frequency values in Table 2 shall not appear in the operation, so the structural resonance will not occur. The first three-order modes of vibration of laser head are shown in Fig 5.

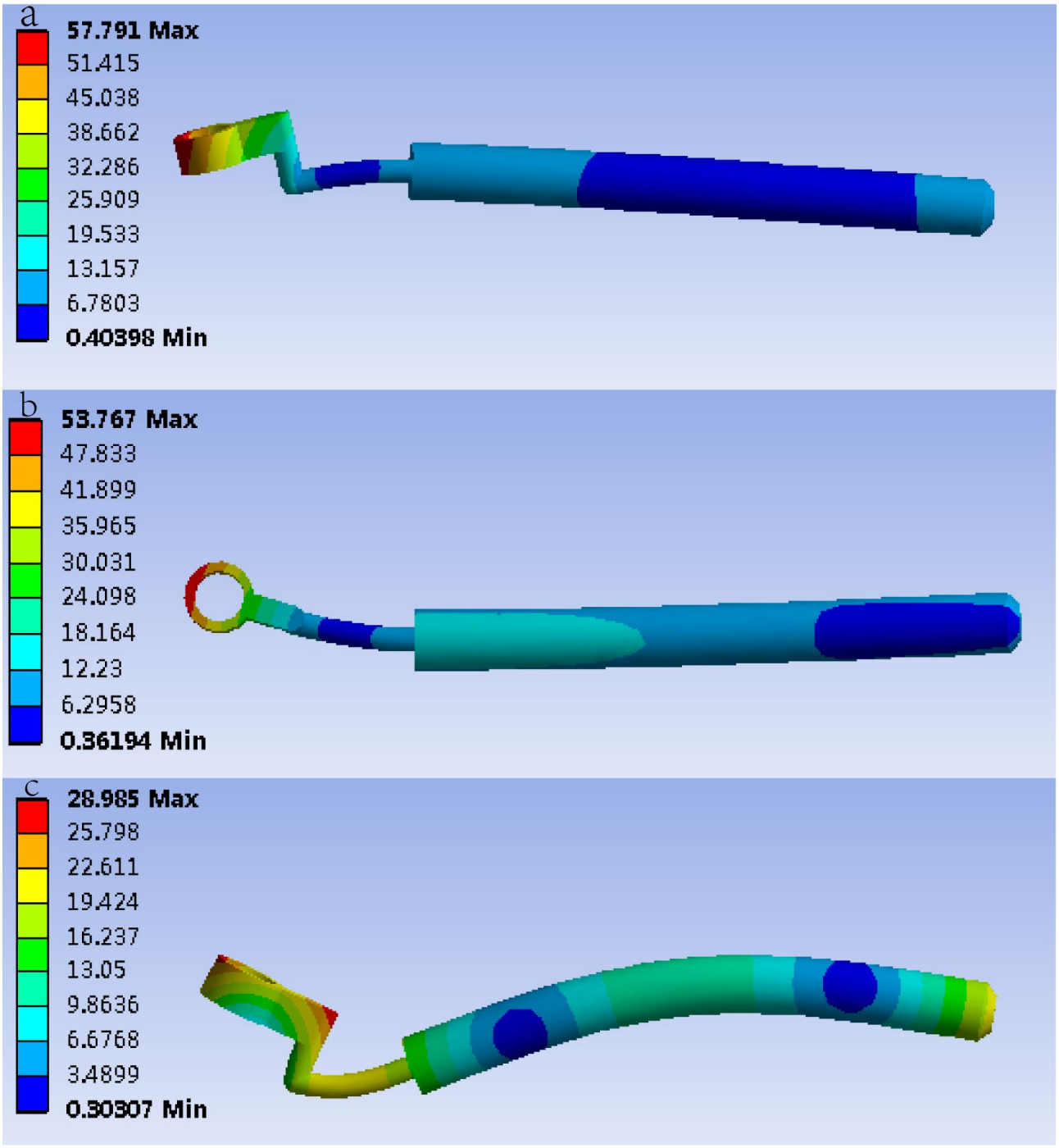
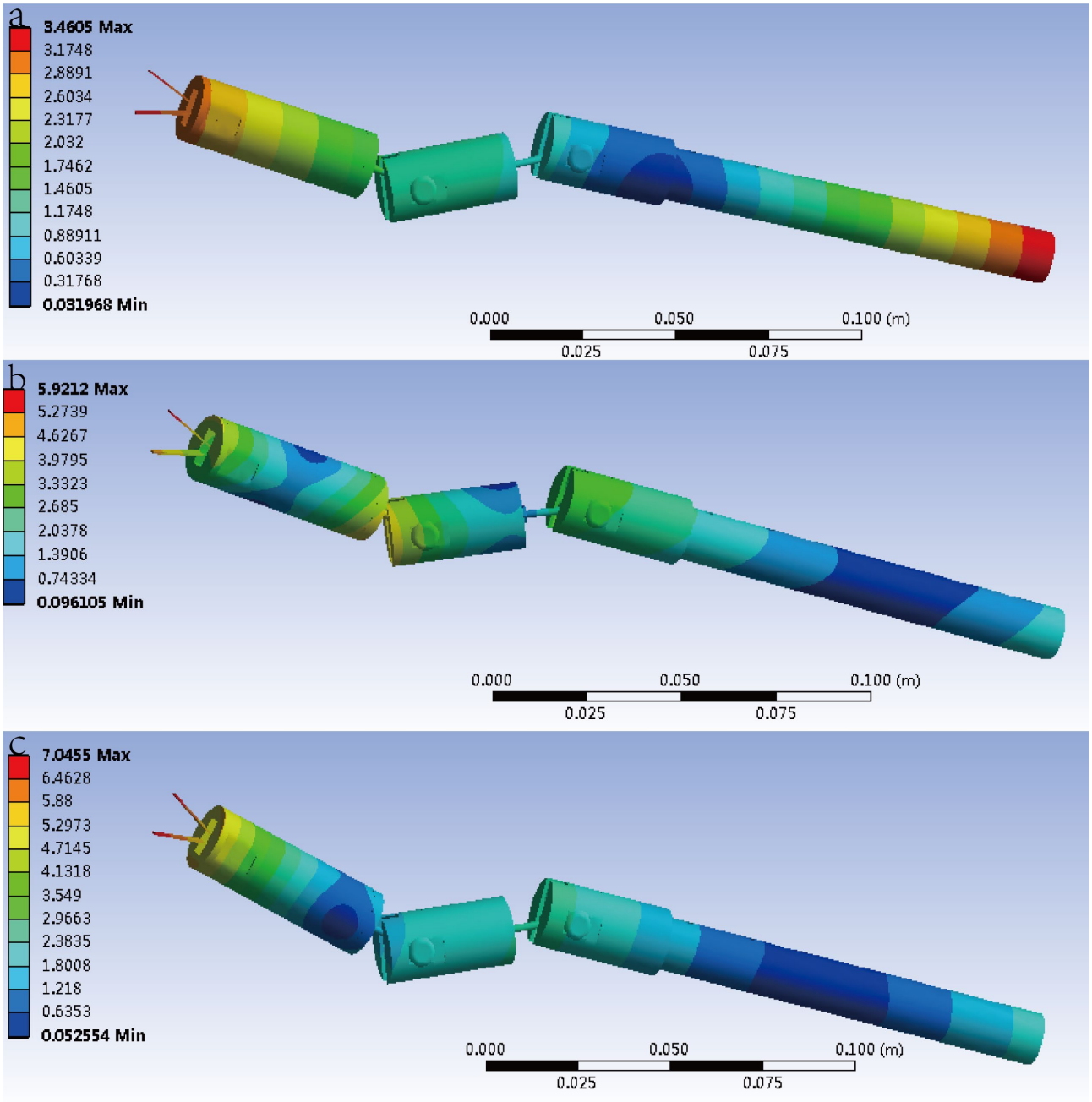


Fig.4 Modal analysis of the left arm; a:first-order modal frequencies of the left bimanual robot; b. second-order modal frequencies of the left bimanual robot; c: third-order modal frequencies of the left bimanual robot



212 Fig.5 a:first-order modal frequencies of the laser head; b:second-order modal

213 frequencies of the laser head; c:third-order modal frequencies of the laser head

214 4. Vitro experiment

We conduct the vitro simulation experiment of the bimanual robot in a laboratory platform for fenestration and drainage of hepatic cyst (Fig.6).

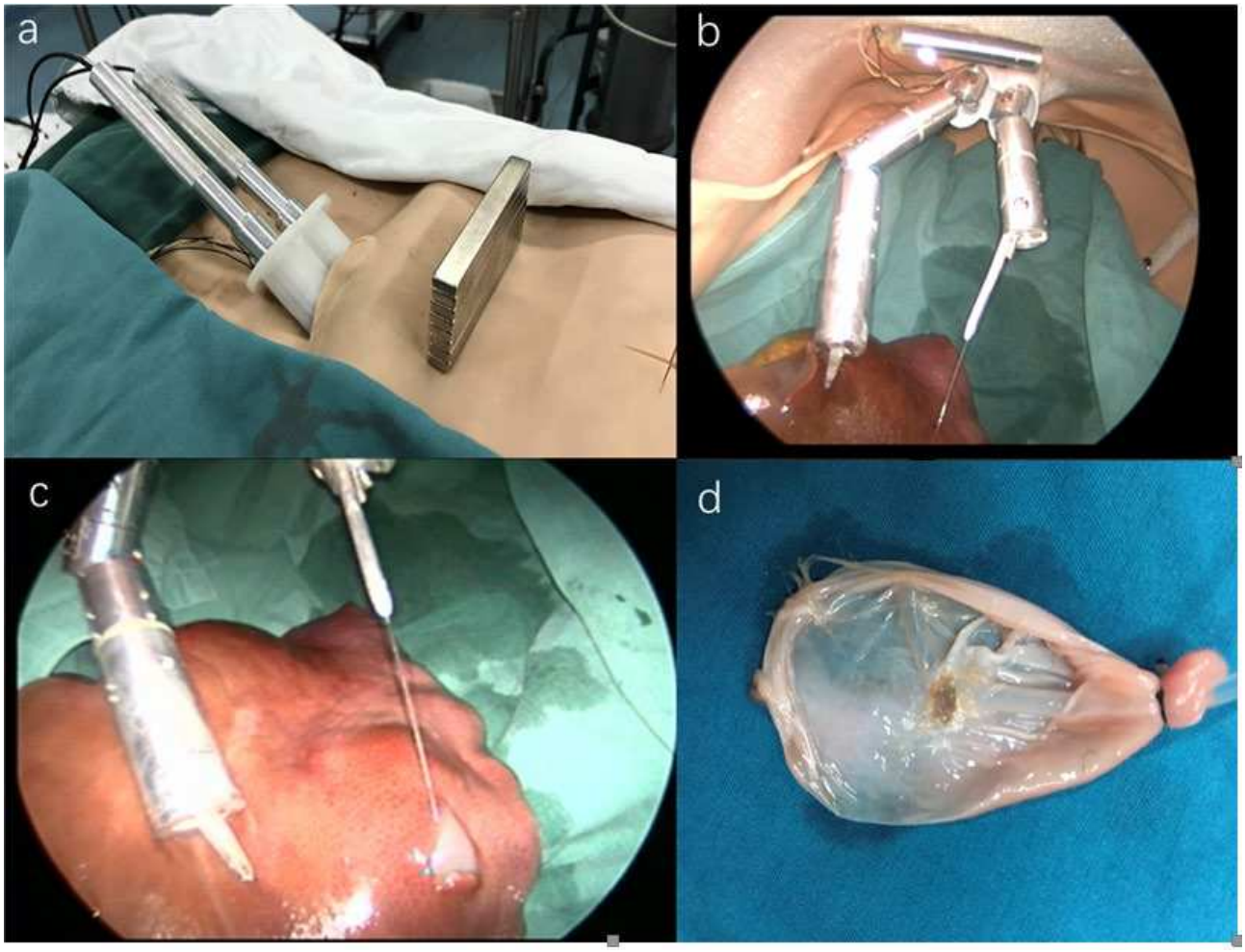


Fig.6 vitro experiment of fenestration and drainage of hepatic cyst

A laparoscopy training platform, called the ex vivo real-liver laparoscopic training system, was used as the bench test in this study. A fresh pork liver was obtained from the slaughterhouse. The swim bladder is tied tightly after filling with water and inserted into a subcapsular to simulate liver cyst. A 40mm high external magnet is used to anchor the mini-magnetically laparoscope. Then the bimanual robot is placed into the abdomen through a 22mm×15mm trocar in the middle abdomen. The umbilical is placed a 10mm traditional endoscopic trocar, which for observing the movement and

operation process of the bimanual robot by laparoscope. The left arm grippers the cyst wall first, and the laser fiber load in right arm can cut the cyst wall. Five cases of fenestration and drainage of hepatic cyst are performed by bimanual robot. The completion of the experiment is shown in table 3.

Table 3 result of vitro experiment

Number	Success of imbed in abdomen	Instrument interaction	operate fluency	Gripper strength	Operate success	Operate time(min)	Setup time(min)	cause of failure
1	Yes	no	Yes	enough	yes	22	6	-
2	Yes	no	Yes	poor	no	2	7	Laser fiber damage
3	Yes	mild	Yes	enough	yes	21	5	-
4	Yes	no	Yes	enough	yes	20	5	-
5	Yes	no	Yes	enough	yes	20	4	-

Discussion:

Laparoscopic was been used to perform appendectomy and cholecystectomy earlier(27). Then, the laparoscopic surgery technique has continued to grow quickly. Laparoscopy was soon applied to abdominal surgery(28)and urology(29) and the security has been verified(30, 31).Over the last decades, surgeons have been committed

to the improvement of laparoscopic technique. Comparing with conventional laparoscopy, single-incision laparoscopic surgery has shown lower pain scores and a shorter hospital stay(32, 33). SPLS has achieved an effective and safe therapeutic effect on both benign disease and cancer(34-37) and reduce the risk of organ injury, hemorrhage, and postoperative adhesions(38, 39). Proponents argued that single-incision laparoscopic surgery will supersede conventional multiport laparoscopy by overcome the shortcoming of conventional multiport laparoscopy, in the same way that laparoscopic surgery superseded the open alternative. But the SPLS not widespread in surgery because the motion limitations and clashing of surgical instruments due to crowding and lack of triangular dissection. With the development of robotics, research team have realized that robotics can effectively solve the problems faced by SPLS. Most robot-assisted MIS systems are equipped with a master–slave teleoperation system for convention multiple ports Laparoscopic surgery. including da Vinci®, MiroSurge, Sofie, Robin Heart, and MicroHand A were developed by leading research teams in the world(40). Growing number of teams are working on convenient single-port laparoscopic robots. The application of single-incision laparoscopic surgery had most commonly been used for cholecystectomy within general surgery. So, there are some team using the Da Vinci Si Surgical System to operate cholecystectomy(41, 42). A team has used Da Vinci SP for a 59 years old woman with chronic calculus cholecystitis to operate cholecystectomy in 89 minutes recently(43). Although the cholecystectomy was completed successfully using the Da Vinci Si Surgical System or Da Vinci SP, such a substantial cost is not suitable to be extended to all patients requiring cholecystectomy.

Furthermore, due to Da Vinci System large dimensions, it has a negative impact on the operating room and the setup before a surgical intervention is a very time-consuming process. Besides, most of these surgery robot systems are bulky, expensive, and have a long learning curve, making them difficult to promote in primary hospitals.

This paper describes a novel handheld bimanual robot that can be ease of set up and use by a single port of 28mm. The robot carries magnetic anchored camera and 980-nm diode laser result in don't need an extra port to set laparoscope and tissue scissors. Each robotic arm was designed with a maximum diameter of 14mm and a total length of 330mm plus the extra DOF provide by hands, resulting in an adequate surgical workspace within the patient's abdomen. The hybrid actuation approach results in a convenient trade-off between the complexity of the robotic structure and the workspace, while still guaranteeing dexterity and telemanipulation capabilities for the surgeon. The major contribution of this work is the operating triangle provided by the robot itself can solve the problem of the interaction of intra-abdominal instruments. This structure avoids spending more time to setup time also. Our bimanual robot takes only four to seven minutes to setup, we argue that in real surgery will still be much less than the current robot setup time. When the robot is not working state, its arms are parallel and it can easily enter the abdomen. The whole structure of the robot adopts rigid connection, can supply for high torque transmission capability and avoid the instability of cable connection.

To verify the feasibility of the bimanual robot, three kinds of tests were performed –kinematic analysis, dynamic simulation, modal analysis, and vitro experiment – with

each obtaining satisfactory results. Kinematic analysis suggests the robot can provide enough workspace and modal analysis suggests that the robot will not cause additional damage to the target and itself due to resonance. We can find the speed and force of gripper changing smoothly in dynamic simulation. So, the gripper will not cause secondary damage. Although in the in vitro experiment, the failure of the experiment was caused by the damage of the laser fiber, we realize that was not caused by resonance, but by the improper operation. Comparing with the compact single-site robotic surgical system(44), the structure of our robot is simpler and portable, and the incision size for setting the bimanual robot is smaller because the operation of the triangle is forming in abdominal while the triangle outside of abdominal need bigger incision size. With the handheld, surgeons don't need a operate platform(45). This will lead to lower robot manufacturing costs, which in turn will reduce patient costs.

The bimanual surgical robot loads a laser knife for incising tissue, it can cut and stop bleeding without contact tissue. The high-frequency electrical surgical knife will generate complex electromagnetic environments that will affect the normal operation of electronic equipment. In serious cases, the function of electronic equipment will be lost or even damaged. And once the electrode breaks down in contact with the patient, it is easy to cause electric burning, burns and fire hazards(46). But, those drawbacks will not occur in laser knife because of the non-contact way and its physical characteristics.

However, the strength of the robot is not enough to operate other procedure, further research would need to be made by improving the structure designation(47). Future

works will focus on improving system accuracy and more driving force. In addition, we also need to improve the robotics arm execute speed to ensure that the robot can efficiently complete the precise operation during the surgery. At the same time, for the convenience and practical use of surgeons, a good interactive system should be designed, and finally a robot can be operated by one physician. While much work remains to be done, the bimanual robot still achieved the specific design goals. We expect more advanced surgical tasks with in vivo animal models will be performed in the near future.

Conclusion: This bimanual surgical robot has the potential to become a surgical instrument for simple intraperitoneal surgery. It can provide a small, portable and inexpensive surgical robot system.

Methods:

Mechanical design:

The bimanual robot consists of two arms (Fig.7). The left arm consists of three motor units, two revolute joints and grippers. The right arm contains two revolute joints, two motor units and a laser fiber port. Shoulder actuation units can form the shoulder triangle by moving the elbow actuation unit range 0 to 90 degrees. Elbow actuation units can form the elbow triangle by moving the gripper actuation unit or laser head range from 0 to 90 degrees. The diameter of left and right arms is 14mm, the length is 330mm, and the weight of one arm is about 200g. The bimanual robot can be inserted into the abdominal cavity in a columnar constriction (Fig.1b) through a traditional laparoscopic port. In order to meet the requirements of forming an operation triangle

during operation, the robot can unfold a shoulder-elbow shape when arriving at the work area.

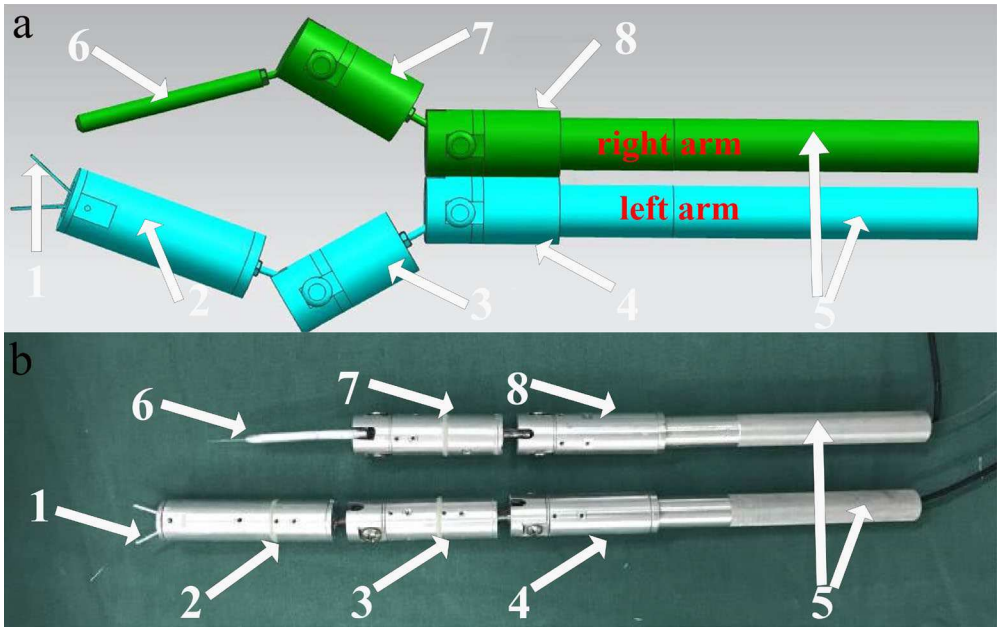


Fig.7 bimanual robot. (1=gripper, 2= gripper actuation unit,3= elbow actuation unit(left),4= shoulder actuation unit(left),5= Handheld part,6= laser fiber port,7= laser head actuation unit/elbow actuation unit(right),8= shoulder actuation unit(right))

Internal structure：

The internal structure of shoulder actuation unit and elbow actuation unit of left arm is same as the right arm (Fig.8). Those actuation unit driving force is provided by stepper motor. The motor that drives the rotation of the bottom bevel gear and top bevel gear, then driving the swing of the next part through the axis by the Z-connecting rod. Gripper actuation unit also use stepper motor to supply power, the motor and sleeve is connected by threaded. So, sleeve can move up and down when the motor rotating and inversion. In addition, as the sleeve moving, the connecting rod is pulled through the lower and middle axis to move, which causes the gripper to create a grasping and opening motion

around the top axis.

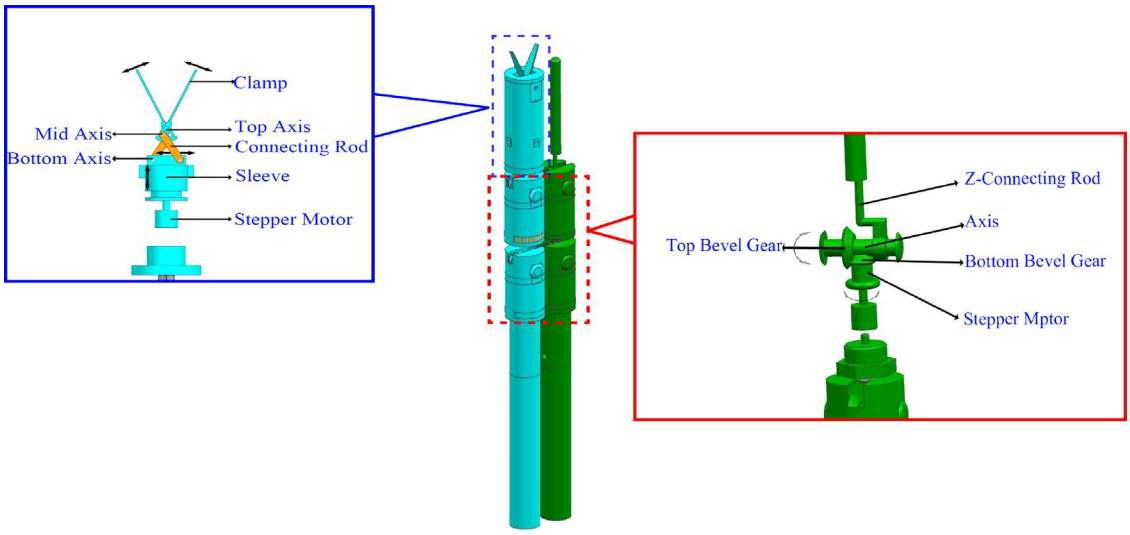


Fig.8 internal structure of bimanual robot

Data processing:

The workspaces of the bimanual robot were analyzed by MATLAB R2019a, kinematic simulation analysis and Modal analysis were analyzed by NX 12.0.

Supplementary information:

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Authors' contributions:

Each author is expected to have made substantial contributions to the conception and design of the work. ZF, DHD, YW, TM completed the vitro experiment, ZF have drafted the manuscript, HYZ and YL contributed to the drafting and revision. DHD and HC essentially contributed to the data acquisition, processing and analysis. All authors read and approved the final manuscript.

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Not applicable. There is no clinical trial or animals experiment.

Consent for publication:

Not applicable. There is no volunteer.

Availability of data and materials:

All data generated or analyzed during this study are included in this published article.

Competing interests:

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper;

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Figures

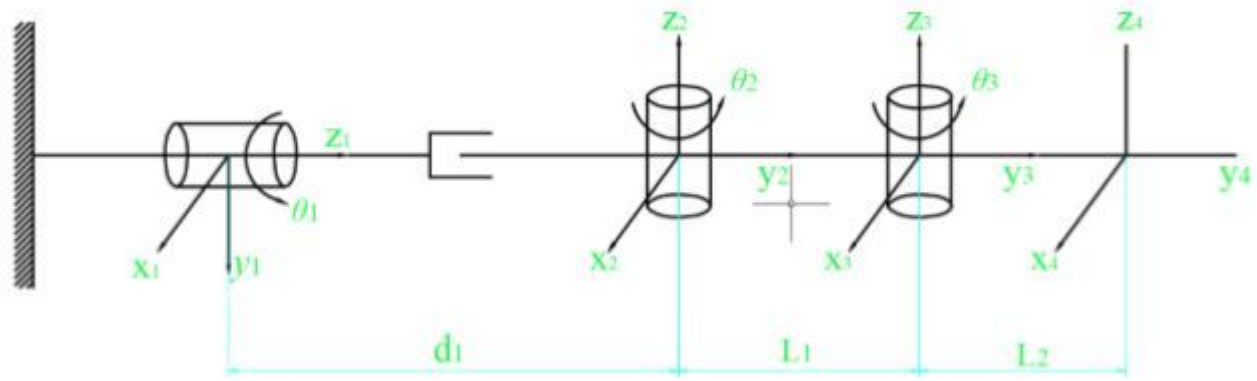

Figure 1

Coordinate system of each link of the robot

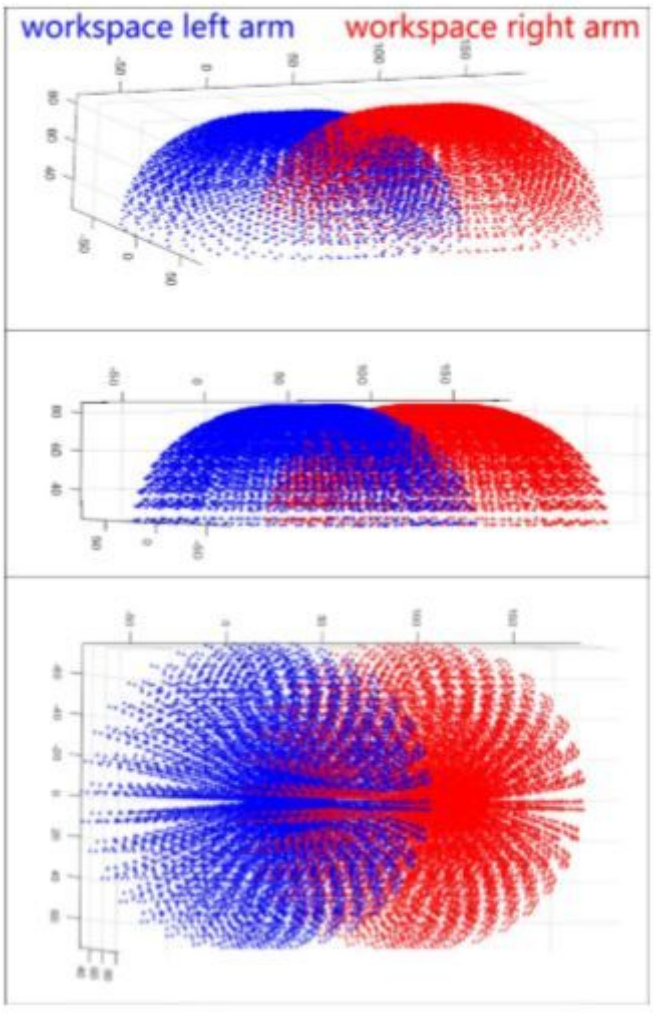

Figure 2

The workspaces of the bimanual robot

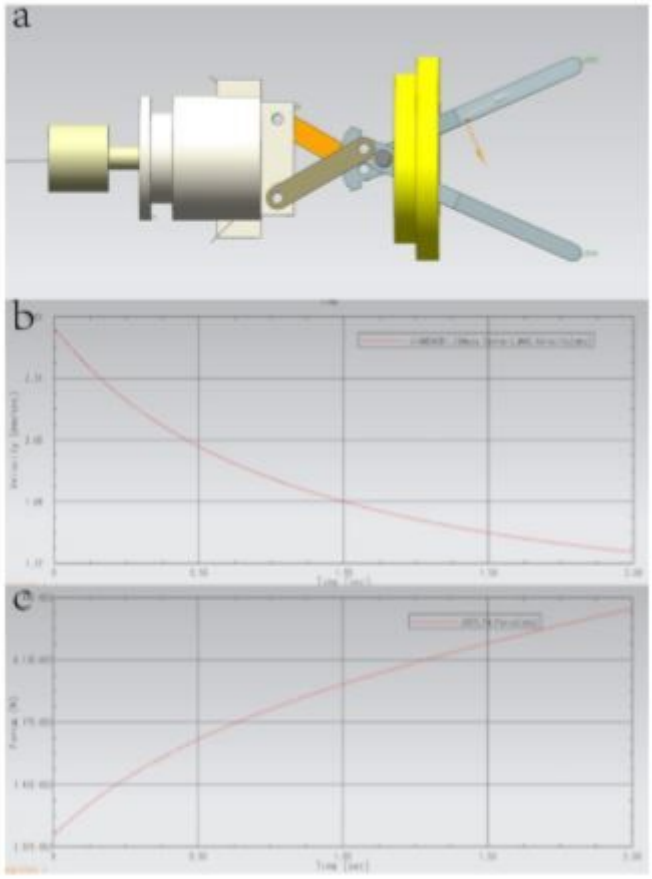

Figure 3

kinematic simulation analysis

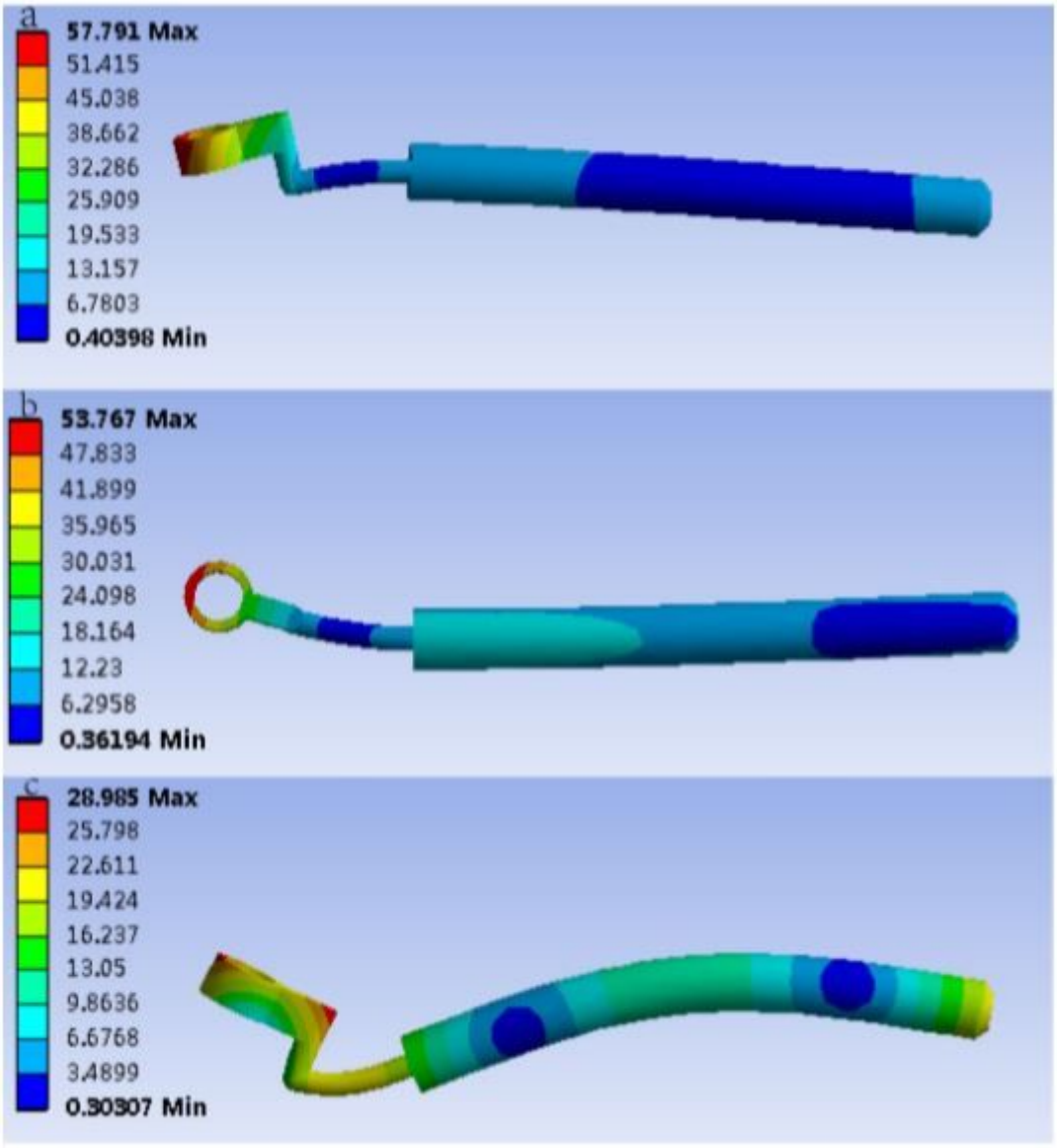

Figure 4

odal analysis of the left arm; a:first-order modal frequencies of the left bimanual robot; b. second-order modal frequencies of the left bimanual robot; c: third-order modal frequencies of the left bimanual robot

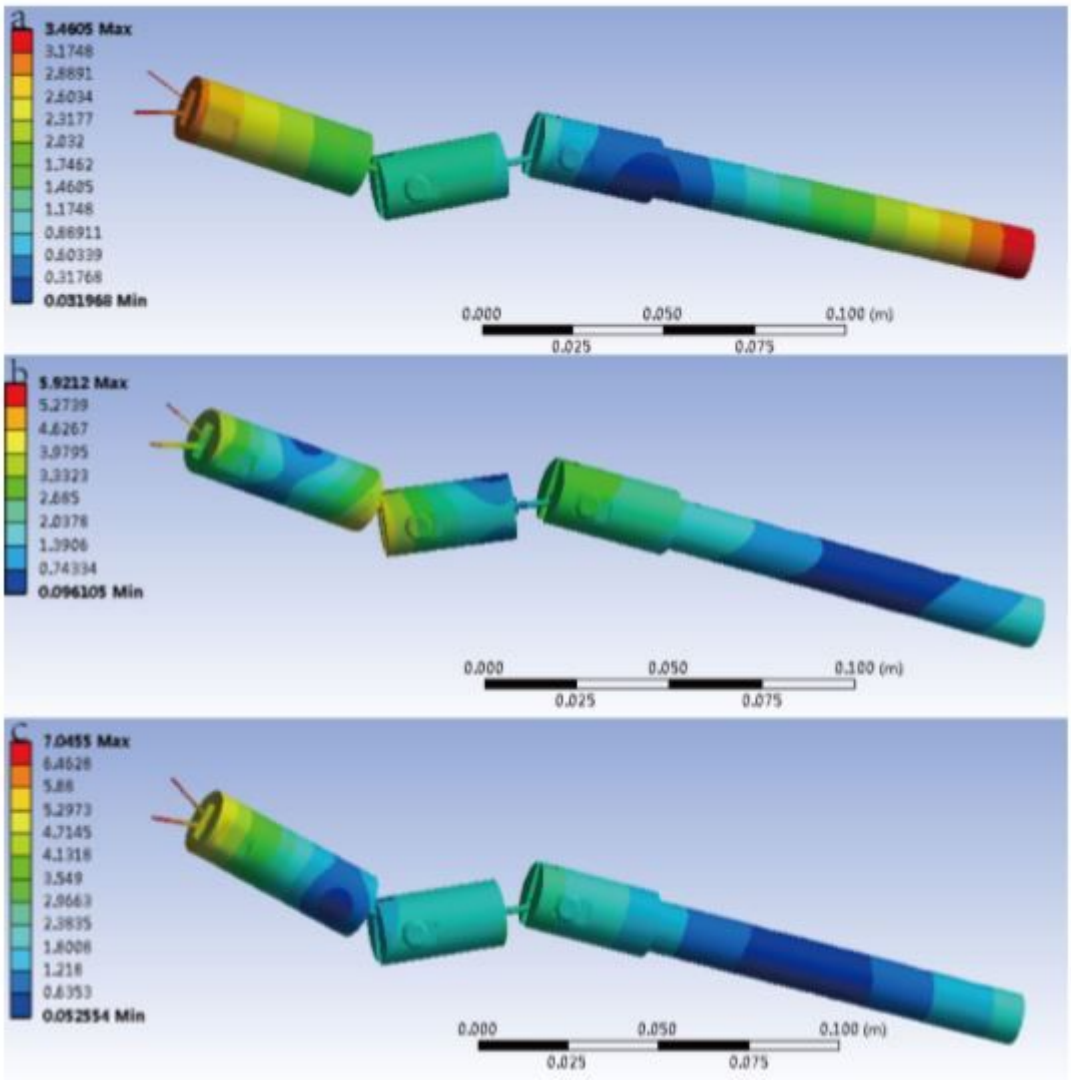

Figure 5

a:first-order modal frequencies of the laser head; b:second-order modal frequencies of the laser head; c:third-order modal frequencies of the laser head

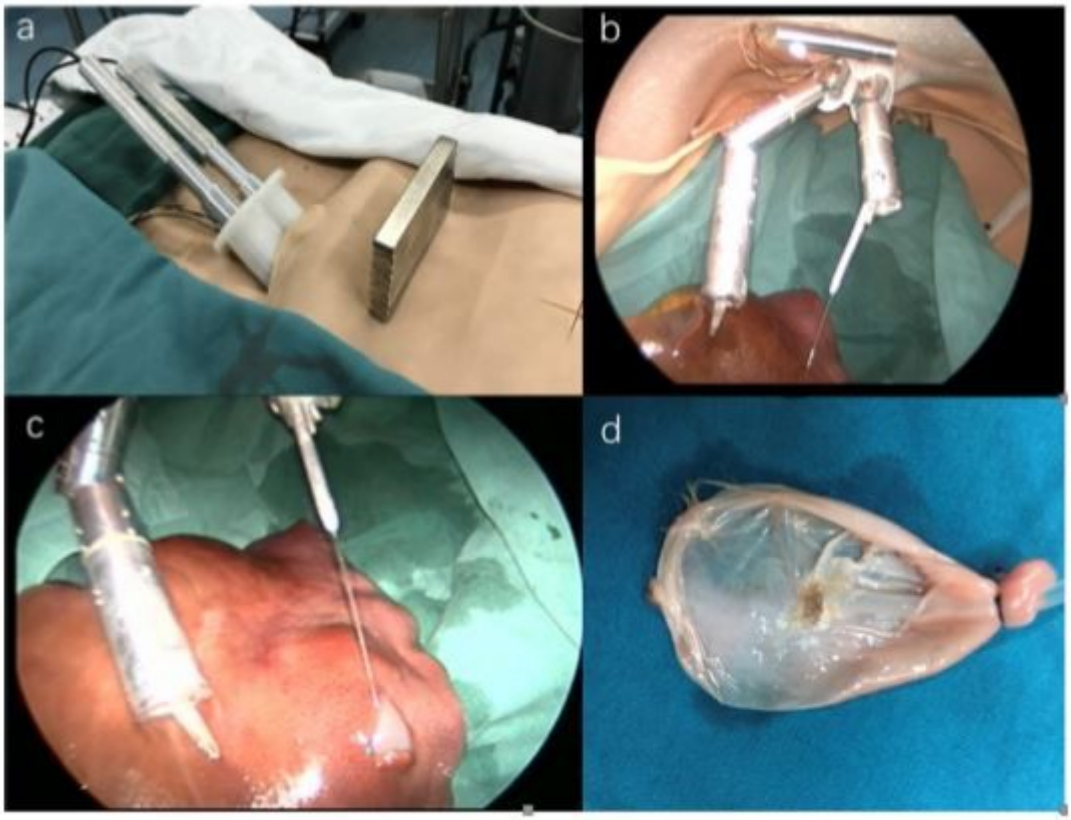

Figure 6

vitro experiment of fenestration and drainage of hepatic cyst

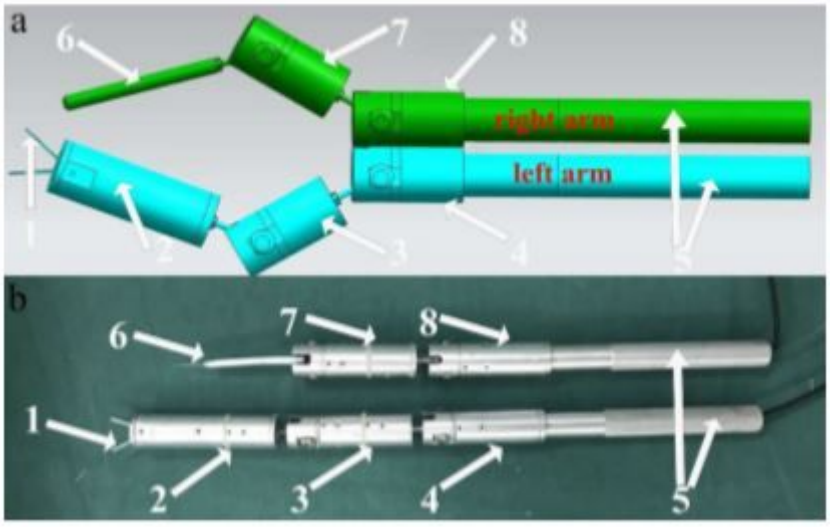

Figure 7

bimanual robot. (1=gripper, 2= gripper actuation unit,3= elbow actuation unit(left),4= shoulder actuation unit(left),5= Handheld part,6= laser fiber port,7= laser head actuation unit/elbow actuation unit(right),8= shoulder actuation unit(right))

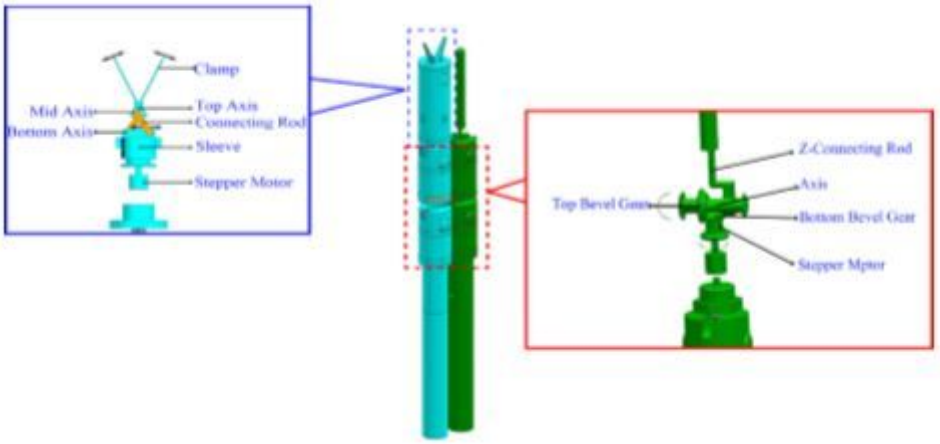

Figure 8

internal structure of bimanual robot