Surgical Robot System for Single-Port Surgery with Novel Joint Mechanism

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Abstract—Single-port surgery is a new surgical method performed by inserting several surgical tools and a laparoscope through an umbilical incision. Compared with conventional laparoscopic surgery, the smaller incision in this procedure produces a lower amount of trauma, which leads to shorter hospitalization. However, with the current laparoscopic tools and surgical robots, the surgeon must overcome several difficulties such as a limited range of motion and collisions between the surgical instruments and the laparoscope.

This paper proposes a new surgical robot system for single-port surgery that uses a novel joint mechanism. The proposed joint mechanism is suitable for surgical instruments with multiple degrees of freedom (DOF). Thus, it can prevent hysteresis of the joint and achieve more accurate motion with a large force. A 6-DOF surgical instrument with this joint mechanism can avoid collisions between surgical tools or arms and approach the surgical target more easily than a conventional straight surgical tool. The external arm with 2-DOF passive joints can extend the workspace of the system during surgery. Preliminary tests and validations were performed with a prototype of the system.

Index Terms—Medical robotics, surgical robot, minimally invasive surgery, single-port surgery,

I. INTRODUCTION

MINASIVENESS of laparoscopic surgery has gradually been reduced through the development of equipment and techniques. As a result of these efforts, single-port surgeries are commonly being performed by inserting a large number of surgical instruments and a laparoscope through a 2–3-cm hole in the patient’s umbilicus. Because the umbilicus is located in the center of the abdomen, it provides easy access to organs, and the absence of special blood vessels and nerves can reduce pain and complications. In addition, there are almost no scars because of the fast postoperative recovery and a sealing effect [1]. However, when a conventional surgical tool or robot system is used, numerous pieces of equipment are inserted through the hole, with crossed positions. This results in several disadvantages such as collisions between the tools and difficulty accessing lesions. Because of this, surgical techniques are difficult and require long periods to master compared to general laparoscopic surgery. Moreover, the accuracy of a surgery can decrease and the operating time can be longer [1].

Recently, single-port surgery has received attention in the medical community, and various manual surgical instruments have been developed [2]–[4]. The manual surgical tools that are being developed focus on designing articulating tool tips to prevent collisions outside of the patient’s abdomen. Camera system for single-port surgery is also developed [5]. There have been several clinical trials of single-port surgeries using the da Vinci system [6], [7], a large external arm that passes through the hole and moves continuously during surgery, which causes frequent collisions. To overcome these problems, several robot systems for single-port surgery have been developed. The bimanual robot system developed by Paulo et al. [8] and the robot system using a stackable 4-bar linkage developed by Lee et al. [8] could be used for single-port surgery. Moreover, multi-DOF robotic systems are developed for more complex surgery. At Columbia University, Nabil Simman et al. developed a surgical robot system with multiple degrees of freedom (DOF) using a backbone and multiple disks for laryngoscopy or natural orifice transluminal surgery [10]. At Purdue University, Peine et al. performed a submucosal dissection using their surgical robot system with a 9-DOF flexible surgical instrument [11]. However, these systems sacrifice some of the force at the tip of the surgical instrument for increased DOF within a small diameter.

In this paper, to overcome the disadvantages of single-port surgery, a new surgical robot system is proposed that has minimal movement outside the patient’s abdomen while maintaining the required DOF and tip force for surgery. The proposed surgical robot system consists of surgical instruments and an external arm. The specially developed surgical instruments have elbow joints that use a novel joint mechanism, which allows them to easily approach a lesion using only movements in the intraperitoneal cavity. The external arm consists of an active joint for translational motion of the surgical instrument and 2-DOF passive joints to extend the system workspace during surgery.
II. SYSTEM DESCRIPTION

In the design of surgical robotic systems for single-port surgery, the biggest differences compared to conventional laparoscopic surgery, in relation to problems, involve collisions between arms and the triangulation of the surgical instruments. Therefore, in order to solve these problems fundamentally, it is desirable to minimize the movements outside of the abdomen while moving the tips of the surgical instruments to a lesion. To achieve this without losing the required dexterity during surgery, the proposed system is designed to move inside of the patient’s abdomen, except for translational movement. When the workspace of these internal movements is limited, it can be extended using secondary motions.

A. Overview

The proposed surgical robot system can perform the 6-DOF motions required for surgery, except for the grip motion, just as previous surgical robot systems [13]-[16]. The 6-DOF motions that require during surgery consist of the translational motion provided by the external arm and 5-DOF motion provided by the surgical instrument. When the system does not have sufficient workspace, 2-DOF passive movement can be provided by the external arm. The system has a coupler component with an easily attachable and detachable structure, which allows the operator to replace the necessary instruments during surgery. The driving force is supplied through wires attached to the electrical motors on the base of the external arm. The conceptual design of the whole system is presented in Fig. 1.

B. External Arm

The external arm is responsible for passing the driving force and providing a remote center of motion for the surgical instrument, allowing it to move around the patient’s incision point. In Fig. 1, J1 is a translational joint that can move the surgical instrument, and J0-1 and J0-2 are passive joints for extending the workspace.

We adopted a double parallelogram structure frequently used in other surgical robot systems to establish the remote center of motion. Because two joints of the external arm meet at the remote center, it does not change even if the joint angle of the external arm changes. The driving force is transmitted through wires and rollers using a specific cabling scheme. The adopted cabling scheme was designed to avoid affecting the joint movement of a surgical instrument when the passive joints of the external arm moves as shown in Fig.2.

When the external arm rotates about joint J0-1, there is no affection to the joint of a surgical instrument, because all of the wires do not move. However, when the external arm rotates about joint J0-2, wires move because of winding at the rollers with a change of angles. In that case, the angles between roller 1 and roller 2, roller 2 and roller 3, and roller 4 and rollers 5 and 6 will change. To avoid rotating a connector pulley because of an angle change, we designed the radius of roller 3 to be twice the radius of rollers 1 and 4. Therefore, the amount of wire wound at idle rollers 1 and 4 is the same as the amount released idle roller 3. Thus, changes in the external arm’s joint angle do not affect the joints of the surgical instrument. In addition, because the motors do not move when J0-2 rotates, the control burden of the system is minimized with this cabling scheme. Because many kinds of surgical instruments are required during surgery, it has to have an easy attachment mechanism. Therefore, connecting pulleys make it possible to easily assemble the actuating pulleys of a surgical instrument. When a motor rotates, the wires are moved in opposite directions, and the connecting pulley rotates to actuate the joint of the surgical instrument. Seven motors are arranged at the bottom of the external arm to actuate the translational motion of the external arm and 6-DOF (with grip) motion of the surgical instrument.

C. Surgical Instrument

Because there is only translational motion in the external arm, a surgical instrument has to have more than 5-DOF motion to achieve a natural motion of the tool tip in the 3-dimensional Cartesian space.
The structure of the surgical instrument provides an external rotation (joint 2), elbow joint (joint 3), internal rotation (joint 4), wrist joint (joints 5 and 6), and grip, as shown in Fig. 1. The 3-DOF position of the wrist joint is determined by the translational joint provided by the external arm and joints 2 and 3 of the surgical instrument, while the 3-DOF angle is determined by joints 4, 5, and 6. Because of the nature of single-port surgery, numerous instruments are inserted through a hole and expanded in the abdominal cavity. However, an elbow joint can create a triangulation similar to general laparoscopic surgery by gathering the tips of the instruments at a lesion. In addition, suturing can be easily performed by rotating the wrist joint with an inner rotation.

Each joint of the surgical instrument is activated by the pulley built into the coupler combined with the external arm. The 2-DOF rolling joint (joint 2, joint 4) is driven by rotating shafts using bevel gears, while the other joints are driven by pulling and releasing the wires using the pulley. The structure of each joint will be explained in more detail in chapter 4.

D. Forward Kinematics of the System

The kinematic structure of the system is shown in Fig. 3. J1-1 and J0-2 are the two passive joints of the external arm. Because these joints are just used to increase the workspace of the system and establish the position of the surgical instrument, only the joints of the surgical instrument and the translational joint are used to calculate the forward kinematics of the system. J1 is a translational motion, J2 is an outer rotation, J3 is an elbow joint, J4 is an inner rotation, and J5 and J6 are the wrist joint.

The D-H parameters of the system are summarized in TABLE I. From these parameters, a homogeneous transformation matrix describing the position and orientation of the wrist joint is given as equation (1). Rotational angle of the wrist joint, \( \theta_4, \theta_5, \theta_6 \), correspond to the roll, yaw, pitch angle of the operator wrist joint respectively.

```
TABLE I
FORWARD KINEMATICS OF THE SYSTEM

<table>
<thead>
<tr>
<th>Joint</th>
<th>( a )</th>
<th>( \alpha )</th>
<th>( d )</th>
<th>( \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>( d_1 )</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>( \frac{\pi}{2} )</td>
<td>0</td>
<td>( \theta_2 )</td>
</tr>
<tr>
<td>3</td>
<td>( \frac{\pi}{2} )</td>
<td>0</td>
<td>0</td>
<td>( \theta_3 )</td>
</tr>
<tr>
<td>4</td>
<td>( \frac{-\pi}{2} )</td>
<td>0</td>
<td>( -L_4 )</td>
<td>( \theta_4 )</td>
</tr>
<tr>
<td>5</td>
<td>( \frac{-\pi}{2} )</td>
<td>0</td>
<td>0</td>
<td>( \frac{\pi}{2} ) + ( \theta_5 )</td>
</tr>
<tr>
<td>6</td>
<td>( \frac{\pi}{2} )</td>
<td>( L_6 )</td>
<td>0</td>
<td>( \theta_6 )</td>
</tr>
</tbody>
</table>
```

\( L_2, L_4, L_5 \) means the length of the link2, link4, link6

(1)

III. NOVEL JOINT MECHANISM

Multi-DOF surgical instrument has to have many joints for dexterous motion. The joint mechanism of a surgical instrument is associated with accuracy, size, and force, so there have been various efforts to improve the performance of surgical robot systems using new joint mechanisms [17]-[22]. In order to realize a high DOF and accuracy in a limited diameter, a wire and pulley are the preferred components for transmitting a driving force. However, it is difficult to realize a high DOF without sacrificing the force and accuracy of the tool tip in a limited diameter. In particular, the elbow joint of the surgical instrument proposed in this paper requires a large torque because of the long distance from the tool tip.

In this chapter, we propose a novel joint mechanism consisting of disks, links, and wires to overcome these problems. The proposed joint mechanism can generate sufficient force with accurate control, without any hysteresis. It is also appropriate for multi-DOF movements by securing the space in the center of the mechanism.

A. Structure of Mechanism

The structure of the proposed joint mechanism is shown in Fig. 4. There are two disks that form the two sides of the joint, a link 1 that has a sliding slot to connect the disks, two link 2’s that connect the sliding slot and disks, and a pin to constrain the relative motion between the disks and sliding slot. A joint can be driven by pulling or releasing a pair of wires attached to the upper disk.

When one wire is pulled by an actuating pulley, the pin moves along the sliding slot of link 1, while maintaining the included angles between the link 2’s and the disks. Because the line of the sliding slot is the same as the center line of the two disks, each disk moves at the same angle relative to the center line. In this joint mechanism, there is no hysteresis because the sum of the lengths of the wire pairs \( (L_1 + L_2) \) is constant.
While this kind of movement is similar to a rolling contact mechanism, it is more convenient to realize and robust compared to the existing rolling contact mechanisms such as a gear mechanism [21] or compliant rolling-contact element mechanism [22].

In the proposed novel joint mechanism, the tension of wires is always equally maintained without any loss of driving force, because there is no hysteresis at the wire. Moreover, because the wires can be attached directly to the disk, the force of the tool tip can be enhanced by expanding the radius of the driving wires without any additional components, such as a pulley. Finally, because the characteristics are maintained regardless of the wire position in the mechanism, several pairs of wires can be used for one joint to enhance the driving force. We used 2 pairs of wires to enhance the force of the elbow joint. Because there is no another component in the center of the joint, securing the internal space makes it possible to pass components for other multi-DOF joints. Unlike previous researches using multiple disks [2],[3],[18],[21] just one pair of disks is required for one joint. Therefore, this mechanism shows better performance in terms of friction and robustness.

B. Kinematic Analysis of the Mechanism

In the Fig. 4, the length of the left wire is \(l_1\), the length of the right wire is \(l_2\), the radius of disk is \(r\), the distance between disks is \(l_0\), and the rotational angle of the disk is \(\theta\). We can easily show that the total length of the two wires is constant, as follows:

\[
\begin{align*}
l_1 & = l_0 - 2r \sin \theta \\
l_2 & = l_0 + 2r \sin \theta \\
l_1 + l_2 & = 2l_0
\end{align*}
\]

Using the variation in the length of the wire to drive the instrument,

\[
\Delta l = 2r \sin \theta
\]

The joint angle is as follows:

\[
2\theta = 2 \sin^{-1} \frac{\Delta l}{2r}
\]  

In equation (6), because \(r\) is the radius of the disk, we can adjust the joint angle by pulling or releasing the wire via the rotation of an actuating pulley.

Fig. 4. Operating Principle of the Novel Joint Mechanism

Fig. 5. (a) Original structure of the new joint mechanism, (b) Simplified structure of the new joint mechanism

For designing the joint parameters, the mechanism can be changed like a crank-slider mechanism by simplifying the area with gray lines, as shown in Fig. 5 (a). In Fig. 5 (b), the relationships between the design parameters are as follows:

\[
d = f(\alpha) = \sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos \alpha} \quad (7)
\]

\[
r_1 \sin(\theta + \beta) + h = r_2 \sin(\alpha + \beta + \theta) \quad (8)
\]

By differentiating both sides of equation (7), we can derive the following equation.

\[
\dot{d} = J(\alpha)\dot{\alpha} = \frac{r_1r_2 \sin \alpha}{\sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos \alpha}} \dot{\alpha} \quad (9)
\]

To avoid a singularity, \(\alpha\) should be larger than 0. From equation (8) and (9),

\[
\alpha = -(\theta + \beta) + \sin^{-1}\left(\frac{r_1 \sin(\theta + \beta) + h}{r_2}\right) > 0 \quad (10)
\]

\[
\sin(\theta + \beta) < \frac{h}{r_2 - r_1} \quad (11)
\]

From the Fig. 5(b), we can also derive,

\[
r_2 > r_1 \sin(\theta + \beta) + h \quad (12)
\]

From equations (11) and (12), the relationships between the design parameters can be derived as follows:

\[
r_1 \sin(\theta + \beta) + h < r_2 < \frac{1}{\sin(\theta + \beta)} + r_1 \quad (13)
\]

To satisfy this condition, we designed the parameters of a joint as shown in TABLE II.

C. Elbow Joint

An elbow joint was designed using the new joint mechanism described above. Fig. 6 shows the developed prototype of the elbow joint. A second prototype of the elbow joint was developed with a more durable structure using two pairs of wires. The range of motion is 0 to 60 degrees, and there is a hole in the center of the joint to secure a space for passing several components.
In order to realize the rotation of the wrist joint (joint 4), the insertion tube for an endoscope is adopted to transmit a torque even when the elbow joint is bent. This insertion tube consists of a coil spring, mesh, and urethane tube. It was designed to have robustness for a torsion, while providing flexibility. Therefore, the rotation of the wrist joint can be easily accomplished just by rotating the inner shaft from the base. The distance between the tool tip and the elbow joint is designed to create enough workspace without any motion of the external arm.

D. Wrist Joint

By adopting a new joint mechanism, a 3-DOF wrist joint with a grip is also proposed. It has a 1-DOF bending joint and 2 grippers that can be driven independently, as shown in Fig. 7 (a). The proposed joint mechanism is applied to the bending joint, and it can bend about axis A. If the two grippers move in the same direction it can bend about axis B, while moving in the opposite direction allows them to grip something.

In Fig. 7 (a), when the bending joint is bent about axis A, the amount of wire wound at idle pulley x1 is the same as the amount of wire released at idle pulley x2. Because of this, the wire does not move the gripper with pulley x3. Thus, the grip motion or bending motion about axis B is independent of the bending motion about axis A. Fig. 7(b) shows a prototype of the new wrist joint.

The proposed wrist joint is similar to the endowrist in da Vinci system [16] and the joint mechanism in [25]. The biggest feature difference with the da Vinci system is the lack of coupling between joints. When the bending joint is bent, the wires for the grippers move because of winding at the rollers. Several previous systems solved this coupling problem using a control. However, the proposed wrist joint minimizes the control burden of the system by solving the coupling problem using a proposed joint mechanism and assistant rollers. The joint mechanism in [25] also solves the problem by a similar method using gears and assistant rollers. However, it is too difficult and expensive to manufacture miniaturized gear. Moreover, the proposed joint mechanism is free from a backlash and issues regarding durability of gear.

To maintain the lengths of the wires that actuate each joint of the wrist while actuating other joints, tensile springs are used as a sheath. These springs are inserted in the insertion tube, and rotate or bend with it. Therefore, the wrist joint moves independently of the elbow joint.

E. Coupler

The coupler is a component used to connect the external arm and surgical instrument using the simple sliding slot and hinge, as shown in Fig. 8. There are several actuating pulleys to drive the joints of the surgical instrument with wires, and these
transmit the actuating forces from the motors using connecting pulleys.

F. Assembled Surgical Robot System

Using the implementation discussed above, each part of a surgical instrument was assembled as shown in Fig. 9 (a). The diameter of this surgical instrument is 8 mm, just as in the existing da Vinci system, and 6-DOF motion can be implemented, including the grip motion. The combined surgical instrument and external arm for the surgical robot system are shown in Fig. 9 (b). The motors for driving the system along each DOF are connected to the EPOS2 controller using CAN communication, and the input value of each joint is provided by a PC via a USB port.

As the actuators to drive each joint of the instrument are mounted around the downside external arm, it becomes complex if there are 2 or 3 arms close to the insertion ports. However, if the instruments are operated inside the abdomen with an elbow joint, the space between the external arms can be secured. Because the external arms of the proposed system do not move during surgery except when the workspace is insufficient, the possibility of collision is also decreased. Nevertheless, the size problem of the external arms is still an important issue, so study to minimize the system is required.

IV. PRELIMINARY TEST

In order to evaluate the performance of the developed surgical robot system, three kinds of preliminary tests were performed: a workspace test, joint movement test, tool tip force test.

A. Workspace

A surgical target in single-port surgery is similar to that used in conventional laparoscopic surgery. Therefore, the workspace requirements for a cholecystectomy are used to validate the workspace of the developed system [23]. The driving range of each joint of the system is shown in TABLE III, which allows the workspace of the system to be obtained. As can be seen in Fig. 10 (a), the workspace of the system can satisfy 95% of the requirements for expert surgeon defined in the previous research. Moreover, when combined with the movement of the passive joints in the external arm, the workspace satisfies more than 100% of the requirements for trainee surgeon. The actual measured workspace of the system is shown in Fig. 10 (b).

The surgical tool makes a cone shape around an insertion port in laparoscopic surgery, so we can assume the orientation of the surgical tool. In contrast with the conventional straight tools, the proposed surgical tool makes a smaller cone shape because of its elbow joint. However the proposed system has a wrist joint which can moves ±90° degrees, the orientation of surgical tool tip is enough to satisfy the requirements of conventional surgical tools.
In order to verify the hysteresis and accuracy of each joint, a repetitive driving test was performed using the magnetic field measurement system Aurora. A small sensor is placed in the additional plastic component attached to the moving tip to minimize the influence of the metallic components of the system, as shown in Fig. 11. The movements of each joint are measured for a given sinusoidal input. Fig. 12 shows the measured relationships between the desired joint angles and measured joint angles of the joint during the test.

In the results of the joint movement test, we can find a hysteresis that interferes with the correct movement of each joint. In particular, the hysteresis of the 5-DOF joint of the surgical instrument is larger than that of the translational motion, as shown in Fig. 12. The main cause of this hysteresis lies in the connecting components between the external arm and surgical instrument. We can observe that the actuating pulleys do not move when motors start to rotate despite the movement of the connecting pulleys. In order to check the effect of this error, the movement of the actuating pulley is measured with the same input.

As shown in Fig. 13 (a), the hysteresis of the actuating pulley of joint 3 was also measured during the test. By subtracting the measured hysteresis value from the hysteresis of the joint, we can derive a new graph for connecting components without machining error, as shown in Fig. 13 (b). It shows that hysteresis of joint itself is small enough.

**C. Tool Tip Force**

Because the DOF of a surgical instrument are higher than in a conventional system, the strength at the end of surgical instrument could be weakened. In particular, the elbow joint is far from the tip end. Therefore, a measurement test of the force is needed to verify whether or not the required force can be generated. To focus on the force of the elbow joint, we set up an experiment using a load cell and dummy surgical instrument as shown in Fig 14 (a). This dummy surgical instrument has an elbow joint and outer rotational joint with the same system parameters as previously specified. At the end of the tip, there is a universal joint with a wire hole for measuring the pushing and pulling force in any direction.

The measurement results of this experiment are summarized in TABLE IV. These results show that the pushing and pulling forces are similar at the same angle, and the resisting force is smaller when the joint angle is larger. However, the force in the results is larger than the required force defined in the previous researches [14], [24]. Therefore, it is expected that single-port surgery could be performed using the developed surgical robot.
system without much difficulty.

D. Block Transfer Task

To evaluate the performance of the proposed system, a simple block transfer task was performed using a joystick. A USB camera was used to provide an image of the task. As shown in Fig. 14 (b), volunteers were asked to transfer six blocks from the left peg board to the right peg board, then put it back the position it was. This task is similar to the one of the FLS (fundamentals of laparoscopic surgery) tasks developed to evaluate technical skills during laparoscopic surgery. Five volunteers performed three repetitions of the task, and the time for the completion of each task was recorded. The average time for the task was 432 ± 46s. This result was found to be fairly long in a comparison of previous research results. The major cause of this result is the insufficient intuitiveness of the master interface. Because the mechanical structure of the master interface is different from that of a surgical robot system, it was not easy for the participants to control the system. However, if a proper master interface is developed for the system, we believe that the result can be improved. The absence of depth information and slip in the gripper should be also improved.

V. CONCLUSION AND FUTURE WORK

This paper proposed a surgical robot system that incorporates a novel joint mechanism for single-port surgery. Proposed joint mechanism is designed to achieve enough force and accuracy, and multi-DOF surgical instrument with an elbow joint can easily approaches lesion.

Despite the proposed system’s applicability for single-port surgery, there are several features that must be improved. First, a master interface should be integrated to operate the system, which will make it easier for the system to perform tasks. There is a potential for breaking some small components in the event of a system malfunction, especially in the elbow joint. To reduce the possibility of a malfunction, we will introduce a mechanical limit for each joint to restrict unpredictable motions. In addition to these improvements, the machining error in the connecting components should be fixed to minimize the hysteresis, as mentioned earlier.

ACKNOWLEDGMENT

This work was supported by Korea Evaluation Institute of Industrial Technology (KEIT) grant funded by the Ministry of Knowledge Economy of Korea (No. 10035145), National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 655863) and Meerae Company.

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