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Single-Site Colectomy With Miniature *In Vivo* Robotic Platform

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Single-Site Colectomy With Miniature *In Vivo* Robotic Platform

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***Abstract*—There has been a continuing push to reduce the invasiveness of surgery by accessing the abdominal cavity through a single incision, such as with laparoendoscopic single-site (LESS) surgery. Although LESS procedures offer significant benefits, added complexities still inhibit the procedures. Robotic surgery is proving to be an excellent option to overcome these limitations. This paper presents the experimental results of the single-incision *in vivo* surgical robot (SISR), a multifunctional, dexterous, two-armed robot capable of performing surgical tasks while overcoming the issues associated with manual LESS operations. *In vivo* surgical procedures have been used to demonstrate the efficacy of using a robotic platform over traditional laparoscopic tools. The most recent experimental test resulted in the first successful *in vivo* robotic LESS colectomy utilizing a robot completely contained within the abdominal cavity. In this test, SISR showed significant benefits including access to all quadrants in the peritoneal cavity and improved dexterity.**

***Index Terms*—Laparoendoscopic single-site surgery (LESS), miniature robot, minimally invasive surgery, robotic surgery.**

I. INTRODUCTION

LAPAROENDOSCOPIC single-site surgery (LESS) has been viewed as an important step for reducing the invasiveness of surgical procedures. LESS surgery is performed by utilizing multiple articulating, bent, or flexible laparoscopic tools inserted through a single specialized port, typically placed in the abdominal wall [1]. Although LESS procedures are theoretically better for the patient, inherent drawbacks still cause problems for the surgeons. Current LESS techniques involve crossing the bent tools, resulting in collateral hand movements in which the surgeon's right hand controls the left end effector and vice versa. For these reasons, there has been an increased interest in the use of robotics to improve the outcomes of surgery and to make procedures more precise [2], [3]. Robotic surgery is quickly becoming a viable platform for overcoming the limitations associated with LESS.

Currently, the da Vinci Surgical System (Intuitive Surgical) is the most advanced commercially available robotic system for several types of surgery. Surgical dexterity and visualization are improved by the use of articulating Endo-wrists and 3-D imaging. Recent advancements in the system have allowed for the successful completion of LESS procedures [4], [5]. However, limitations remain including difficulties in repositioning the patient, arm collisions, size, and high cost [6].

Several small laparoscopic tools with externally actuated, robotic end effectors have also been developed. Some notable examples are the COLOBOT, Hyper-Finger, and IREP. The COLOBOT is a pneumatic bendable robotic tip for semiautonomous colonoscopy procedures [7]. Hyper-Finger is a small and highly dexterous active forceps tool that enables more advanced laparoscopic surgery [8]. IREP is an insertable robotic end effector platform with two snake-like arms and a stereoscopic camera designed specifically for LESS procedures [9].

Researchers have also developed completely insertable *in vivo* surgical robots capable of performing complete surgical procedures while addressing the limitations associated with LESS procedures [10], [11]. These two-armed surgical robots can be inserted through a single incision one arm at a time. The robots are then assembled inside the abdominal cavity and remotely operated by a trained surgeon to perform surgical tasks. This robotic approach has advantages for LESS colectomies because this system offers access to all quadrants in the peritoneal cavity, improved visualization and dexterity, and intuitive controls when compared to traditional laparoscopic methods.

Recently, other research performed by the European ARAKNES project has resulted in the development of similar *in vivo* surgical robots, such as SPRINT [12]. SPRINT is similar in architecture to the previous work discussed above and the robot that will be discussed in this paper, single-incision *in vivo* surgical robot (SISR). Both are composed of two arms, each with a single end effector, haptic user interfaces, illuminated stereoscopic vision, as well as teleoperational capabilities. Both robots were designed to have the arms individually inserted through a single small incision. The research presented in this paper has important differences in comparison to the SPRINT robot. SISR is a completely *in vivo* robot, composed of two 4-DOF arms, specifically designed for colectomy procedures. The design approach differs in that all of the SISR actuating motors are contained within the abdominal cavity. The SPRINT robot has 6 DOF on each arm with 4 DOF being actuated by on-board motors and the remaining 2 DOF being externally actuated.

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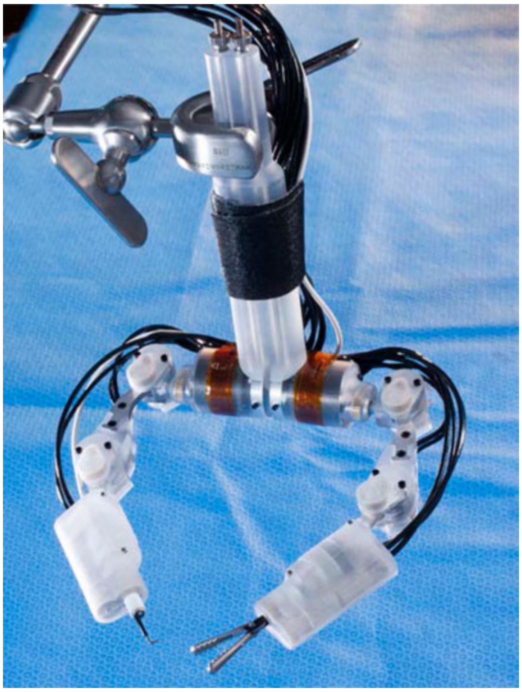

Fig. 1. SISR prototype.

Having all the actuators within the robot results in the robot not constrained by the entry incision. This has important clinical relevance for colectomy and other procedures because the completely *in vivo* robot can be easily repositioned during the surgery, allowing it to operate on large organs. SISR can be easily repositioned in a matter of seconds by rotating or translating the rod that supports it.

In this paper, a surgical robot designed for LESS is presented. Section II includes a brief explanation of the surgical robot platform design. Section III details the *in vivo* results, specifically, the first successful *in vivo* robotic LESS colectomy utilizing a robot completely contained within the abdominal cavity. Section IV analyzes the data that were collected during the experimental surgeries. The conclusions of the paper along with future goals are given in Section V.

II. METHODS

The basic robot design of SISR, shown in Fig. 1, consists of two 4-DOF arms that can be individually inserted into a single 30-mm incision and completely contained within the abdominal cavity. This robot was developed for all LESS procedures, specifically targeting colon resections. A 30-mm incision, although larger than traditional laparoscopic incisions of 5–12 mm, will be placed at or near the umbilicus and still maintain cosmetically pleasing results.

Each arm of the robot comprises of a torso, upper arm, and forearm. The dimensions of these links are 61.9, 50.8, and 81.4 mm, respectively. The overall diameter of the links varies but never exceeds 28 mm. The corresponding joint links were designed to maximize joint range of motion. This yields an individual arm workspace volume of 1856 cm^3 and a bimanual intersecting workspace volume of 776 cm^3. A 2-DOF shoulder joint, located between the torso and upper arm, provides yaw and pitch. A 1-DOF elbow joint also provides yaw. Each end effector has a rotational degree of freedom, along with open/close actuation, if necessary.

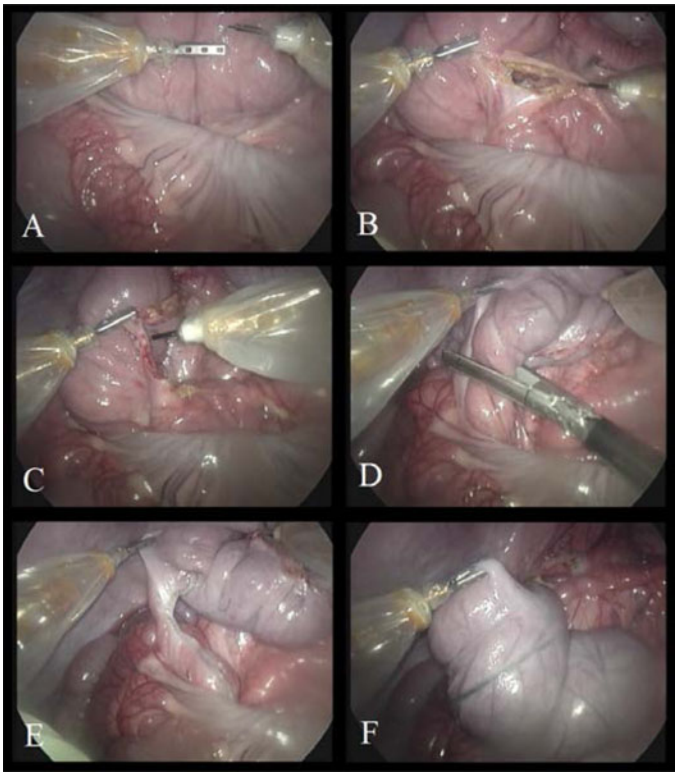

Fig. 2. SISR colon resection screen shots.

To insert the robot, the straight arms are separated and inserted individually through the single incision. Army-Navy retractors are used to lift the abdominal wall to create enough space to insert the robot without disturbing the internal tissue. After the robot is completely inserted within the abdominal cavity, control rods attached to the torso segments are positioned to align the robot arms. An additional support rod is then attached to the control rods to mate the robot arms. Once assembled, a GelPort (Applied Medical) is placed over the support rod and the abdominal cavity is insufflated with CO_2. The support rod protrudes out through the incision and allows the robot to be rigidly supported by the operating table and grossly positioned, if needed.

Extensive details on the robot and user interface design as well as a full kinematic analysis of SISR including theoretical forces, velocities, workspace, and manipulability can be found in [13].

III. EXPERIMENTAL RESULTS

SISR has been tested in multiple nonsurvival surgical procedures in live porcine models at the University of Nebraska Medical Center. All surgical protocol was approved by the Institutional Animal Care and Use Committee (IACUC). Throughout the procedures, specially trained laparoscopic surgeons were on hand to control the robot and assess its efficacy. During these

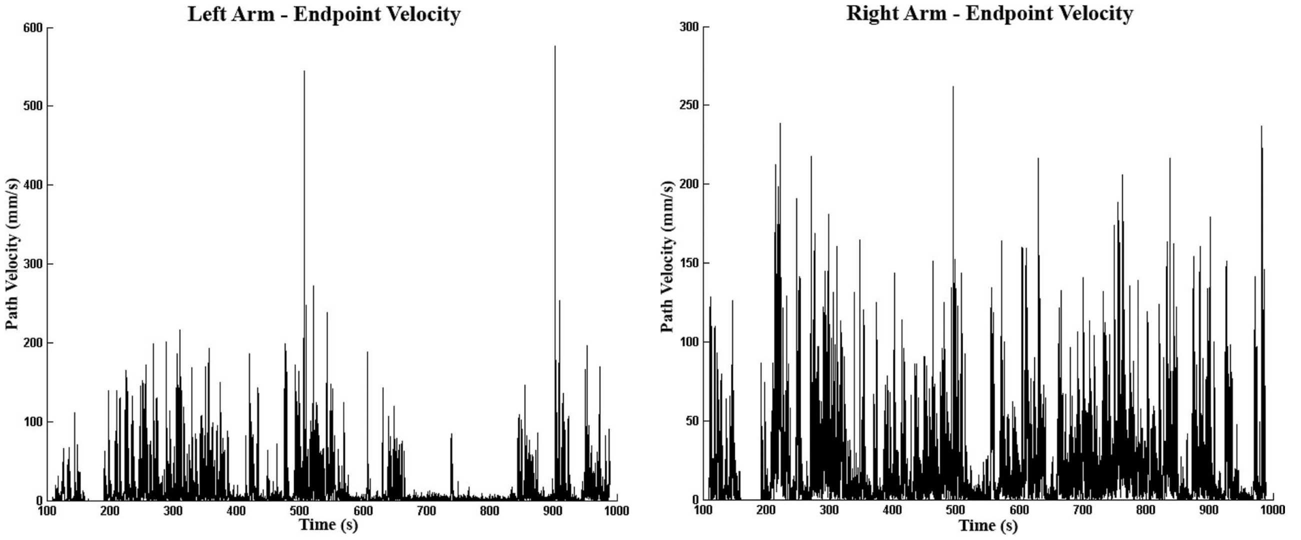

Fig. 3. SISR left and right arm endpoint velocity.

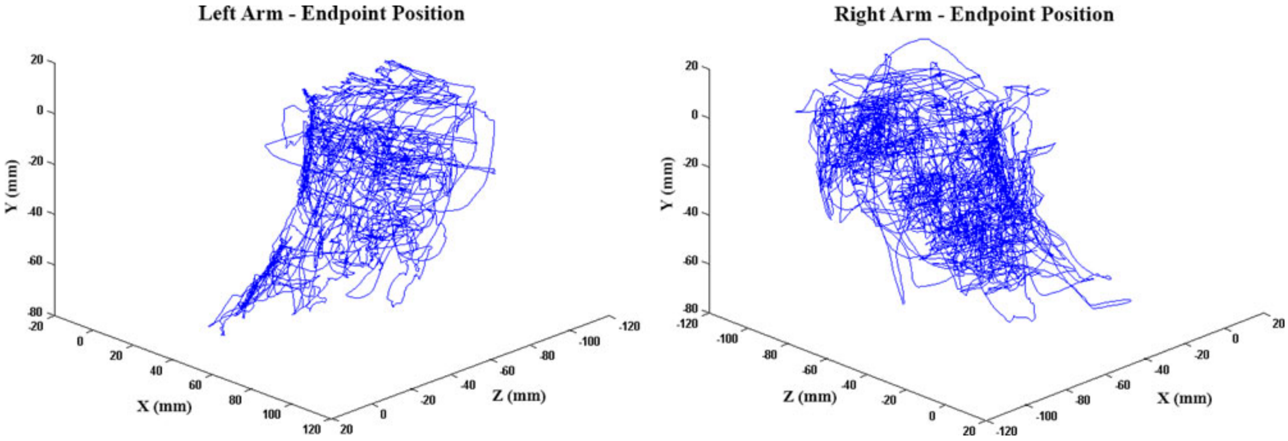

Fig. 4. SISR left and right arm endpoint position.

procedures, a simple insertion procedure was used, the robot operated, and then the robot and specimen were extracted all through the single incision. For each procedure, the left arm of the robot was outfitted with a grasping end effector, while the right arm utilized monopolar cautery. The following details the most recent surgical procedure, a complete robotic cecectomy, and a colectomy procedure specifically targeting the cecum.

A. Insertion

SISR was inserted into the abdominal cavity for the surgical procedure through an incision of 40-mm length on the umbilicus. This incision was purposefully oversized to allow easy insertion for feasibility tests. In the future, the incision could be reduced to the stated goal of 30 mm. As described previously, each arm was individually inserted and then mated to the assembly rod. The entire insertion process took an average of 5 m.

B. Surgical Procedure

During the procedure, a complete cecectomy was performed. As the cecum is located at the end of the colon, only one transection was needed.

At the time of the surgery, the on-board camera was not yet operational so a traditional laparoscope was used to visualize the operation. The video feedback from the laparoscope was recorded and selected screenshots of critical tasks being completed during the cecectomy are shown in Fig. 2. Frame (A) is identification of the colon mesentery; Frame (B) is dissection of the colon mesentery; Frame (C) is mobilization of the colon mesentery; Frame (D) is transection of the colon using a supplementary Endo GIH stapling device; Frame (E) shows the robot assisting with further transection; and Frame (F) is removal of the specimen and completion of the cecectomy procedure. Robotic operating time, defined as the time from the surgeon's first use of the robot until the robot was removed, was approximately 30 min. Typical robotic operating times for colectomies on humans are around 120 min [14].

IV. DISCUSSION

Motor encoder positional data were recorded using LabVIEW during the successful procedure. These data can be transformed into the X, Y, and Z positions of each arm's end effector as functions of time throughout the surgery. The data were filtered and various plots were produced to better visually analyze and to note any observable trends.

The path distance traveled over the duration of the colectomy procedure was calculated for the left and right end effectors. The left arm travels about 12 m, while the right arm travels about 20 m. Analysis reveals that the right arm is much more active than the left arm. Colectomies use the graspers on the left arm to grab tissue and position it, while the cautery on the right arm is used in much more fine repetitive movements as it cuts the tissue. This stretch-and-dissect process is iteratively repeated until the surgery is complete. Because the right arm is much more active, it travels almost twice the overall distance.

Fig. 3 shows the time history plots of the left and right arm endpoint velocities. The peak velocity for left arm is around 550 mm/s and the right arm's peak velocity is close to 250 mm/s. The maximum velocity for the left arm is only reached twice with most of the other peaks topping out at approximately 200 mm/s. The average velocities are 10.8 and 22.7 mm/s for the left and right arms, respectively. Again, the right arm appears much more active. The left arm has several periods of little to no velocity where it would have been holding tissue in a specified position.

Fig. 4 show 3-D plots of each individual arms endpoint position. It is much easier to discern the boundaries of the robotic workspace in these plots even without viewing them as a 3-D object. The plots further verify that the right arm is used more than the left. These plots also show that both arms used up the majority of the workspace volume. Although the robot did not need to be repositioned during the surgery, it appears that the end effectors for both arms were occasionally limited by the inner boundary of the workspace. Improved initial positioning of the current robot or expanded inner workspace of a modified robot could mitigate this problem in the future.

Both plots verify that the right and left arms are used for significantly different surgical tasks. This suggests that nonsymmetric arms could be a desirable design change. Because the right arm is used in slow, fine, articulated movements, it could be designed to be more dexterous and precise. This could include the addition of a compact spherical wrist joint. Conversely, because the left arm is used in quick, coarse, manipulating movements, it would be advantageous to strengthen the arm. This could be accomplished simply through the use of more powerful motors and varying gear ratios.

V. CONCLUSION AND FUTURE WORK

In this paper, details on SISR, a dual-armed multifunctional *in vivo* surgical robot designed specifically for LESS procedures, were presented. A brief overview of the robotic platform was given. Experimental results are also presented. To the best of the authors' knowledge, the robot completed the first successful entirely *in vivo* robotic LESS colectomy.

Future work includes continued *in vivo* surgical experiments as well as an improvement on the reliability of the robot and development of safety protocol to prevent unintentional interactions or other complications. Improvements in the design are continually occurring to improve the robot with a goal to acquire FDA approval to perform a first-in-human procedure.

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