

Article

Development of an ICT Laparoscopy System with Motion-Tracking Technology for Solo Laparoscopic Surgery: A Feasibility Study

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Abstract: The increasing demand for laparoscopic surgery due to its cosmetic benefits and rapid post-surgery recovery is juxtaposed with a shortage of surgical support staff. This juxtaposition highlights the necessity for improved camera management in laparoscopic procedures, encompassing positioning, zooming, and focusing. Our feasibility study introduces the information and communications technology (ICT) laparoscopy system designed to aid solo laparoscopic surgery. This system tracks a surgeon's body motion using a controller, manipulating an embedded camera to focus on specific surgical areas. It comprises a camera module, a camera movement controller, and a motor within the main body, operating connected wires according to controller commands for camera movement. Surgeon movements are detected by an inertial measurement unit (IMU) sensor, facilitating precise camera control. Additional features include a foot pedal switch for motion tracking, a dedicated trocar for main body stability, and a display module. The system's effectiveness was evaluated using an abdomen phantom model and animal experimentation with a porcine model. The camera responded to human movement within 100 ms, a delay that does not significantly affect procedural performance. The ICT laparoscopy system with advanced motion-tracking technology is a promising tool for solo laparoscopic surgery, potentially improving surgical outcomes and overcoming staff shortages.

Keywords: laparoscopy; motion tracking; camera; remote control; ICT

1. Introduction

Laparoscopic surgery significantly minimizes abdominal incisions and reduces traction or contact with the abdominal wall or other intraperitoneal organs during the procedure. This approach substantially decreases adverse physiological effects on the human body compared with traditional open surgery. The benefits of laparoscopic surgery encompass cosmetic advantages due to smaller wounds, reduced surgical complications, diminished postoperative pain, and expedited recovery, ultimately leading to an enhanced quality

of life post-surgery [1–8]. Conversely, the primary drawbacks of laparoscopic surgery are technical challenges associated with inexperienced operators. Given their limited scope positioning and extended length, the requirement for precise manipulations using laparoscopic instruments demands adept techniques. Additionally, the surgeons' vision may be constrained as the scene illuminated by the laparoscope is displayed on TV monitors. Navigating the misalignment between the surgical direction and camera orientation is a technical challenge for inexperienced surgeons.

The anticipated exacerbation of the surgeon shortage in Korea poses a significant threat to laparoscopic surgery, a prevalent surgical method [9,10]. This shortage is further aggravated by the limited availability of surgical trainees to assist in adjusting cameras during these procedures [11]. Furthermore, tasks such as removing contamination from the camera lens with body materials, including blood, tissue, and secretions, and reinserting the camera, are critical during laparoscopic surgery [12]. Addressing these issues requires innovative solutions that empower surgeons while minimizing disruption to surgical workflows. To address these challenges, a device must urgently be developed that supports laparoscopic surgery in alignment with the surgeon's intentions. Enhancing the efficiency of laparoscopic surgery necessitates the development of a device that enables surgeons to adjust the camera's position and cleanse the lens without complications [13–15].

The device's size must be small enough to mitigate surgical space and workflow interference. The system must automatically adjust the camera view by tracking the surgeon's motions. A cleansing module, equipped with hydrophilic/hydrophobic coatings, must surround the camera, and it should rotate dynamically, moving back and forth to effectively clean the blurred lens. In conclusion, applying a system that can adjust and clean the camera will eliminate the need for camera insertion and removal during laparoscopic surgery, and the camera will be adjusted as intended by the surgeon without the help of adjustment personnel.

The Da Vinci surgical system, the dexter robot system, FreeHand, and the Senhance have been developed. These devices have some profits and can assist the laparoscopic camera control. However, they are limited by their size, weight, and price; therefore, further solutions are required for clinical applications. Various developments are being conducted [16–22].

The ICT laparoscopy system must integrate several key components to address the challenges above. A camera module inserted into the abdominal cavity and features camera actuating mechanics driven by motion tracking is essential. Additionally, a camera control module that receives wireless motion-tracking signals from a sensor module must be positioned outside the abdomen. This module regulates the actuation and displays the camera images on the display module. The system must incorporate a motion sensor module that wirelessly captures users' motion information and controls the camera actuator. A display module is necessary to receive and display images on a monitor. A dedicated trocar is required to affix the camera and control modules to the abdomen securely. Lastly, a cleaning module is imperative for clearing the camera lens without removing the camera from the abdomen.

The essential functions and implementation details for each module are as follows. First, the camera module must have a diameter smaller than the trocars affixed to the abdomen. A wire-driving structure is needed to facilitate motion transmission from the external camera actuator's power mechanism. Second, the controller module requires wireless communication capabilities to receive motion-tracking information, a power generator to operate the camera actuator, a control circuit for actuation management, video transmission functionalities, and a fixation mechanism to secure the main body against abdominal movements. Third, the motion-sensing module should include real-time motion-sensing capabilities and a foot pedal switch to turn autonomous motion tracking on or off. Fourth, the display module should receive and present video signals, either wirelessly or via wired connections, to the monitor. Fifth, the dedicated trocar must facilitate the camera module's passage while featuring fixation capabilities. The camera module should have a designated

attachment area for coupling with the cleaning module. Finally, the cleaning module should be designed for easy detachment from the camera module (Figure 1).

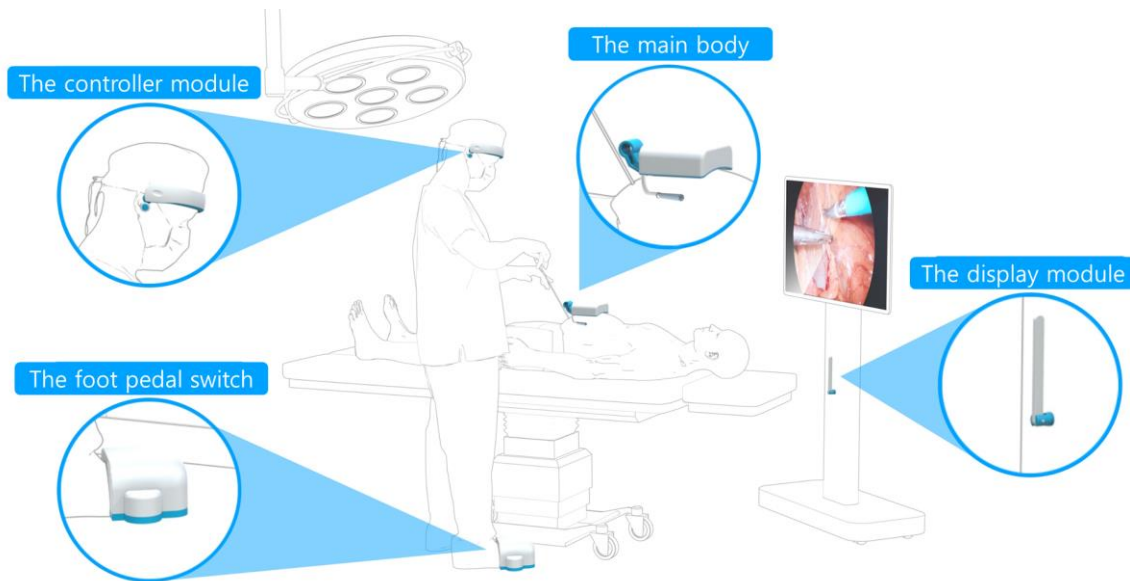


Figure 1. Concept image of the ICT laparoscopy system consisting of a main body that accommodates the camera module, a controller that controls the camera, a foot switch that operates the controller, and a display module that visualizes camera images in real time.

In this feasibility study, a prototype of the ICT laparoscopy system incorporating all the modules was developed and tested to evaluate its functionality and usability.

2. Materials and Methods

2.1. Camera and Camera Controller Modules

The primary structure of the ICT laparoscopy system is composed of the controller module and the camera module. The former encompasses a motor case, which houses a control-printed circuit board (PCB) and a driving motor. Joint and camera segments are integrated within the camera module designed for image capture. This module is inserted into the abdomen for surgical procedures. A connecting part, which links the camera module to the motor case, was developed in three variations: curved, straight, and hybrid (see Figures 2a, 2b, 2c, and 2d, respectively).

Four wires (0.45 mm, stainless steel angulation cable, Medtron Technology, Los Angeles, CA, USA) are utilized to actuate the camera module, with guide springs ensuring the wires maintain a consistent length while navigating the curved path. These wires are strategically positioned at 90° intervals, enabling movement in the up, down, left, and right directions.

The movement of the camera module is facilitated by the rotation of wire wheels, which are connected to the actuating motor (XC330M288T, Robotics Co., Seoul, Republic of Korea). Each wire wheel, encircled by a wire, governs the module's vertical and horizontal motions.

The system's main body was designed to be inserted through a dedicated trocar with a diameter of 12 mm. The insertion range spans from the camera to the straight segment of the connecting part.

Figure 3 illustrates the operational concept of the camera module, which encompasses two primary functions, namely position control and cleaning motion. The control of the camera's position, both horizontally and vertically, is achieved through two pairs of wires, as depicted in Figure 3a. Additionally, the cleaning motion involves the rotation and forward movement of the camera head within the cleaning cover, as demonstrated in Figure 3b.

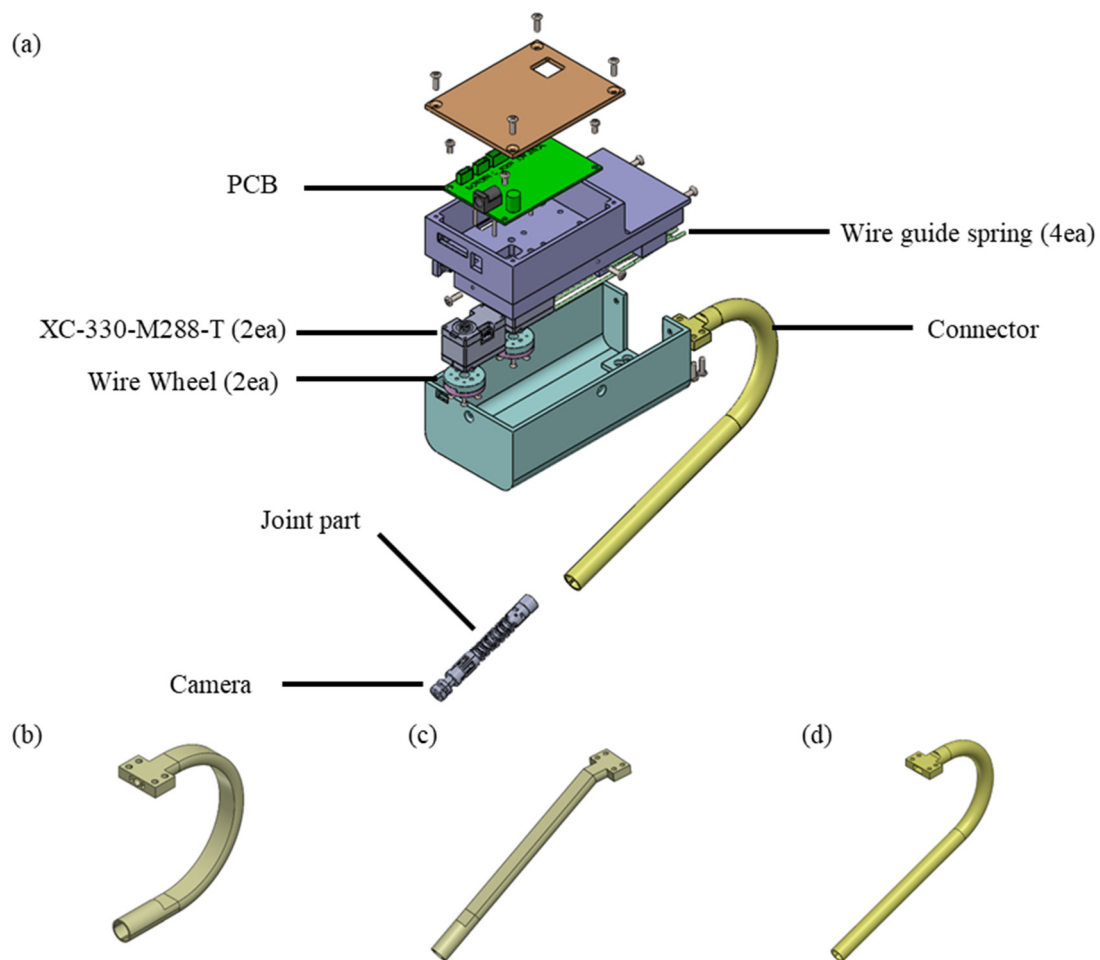


Figure 2. (a) Disassembly diagram of the ICT laparoscopy system's main body, including the camera and control modules. The (b) curved, (c) straight, and (d) hybrid connectors connect the camera module to the camera control module.

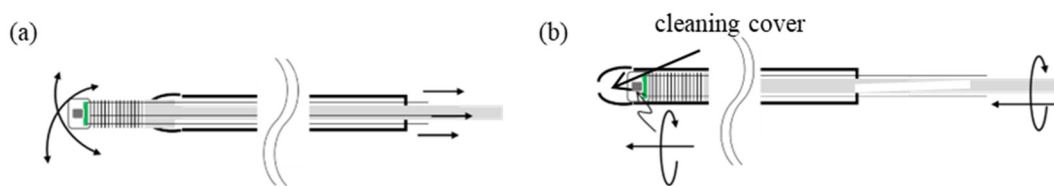


Figure 3. Operating concept of the camera module. (a) Two pairs of wires control the camera's vertical and horizontal position, and (b) the cleaning motion is executed through the rotation and forward movements of the camera head within the cleaning cover. When the camera lens rotates and moves forward within the cleaning cover, the lens is cleaned by contact with the cleaning cover.

The camera module of the ICT laparoscopy system, illustrated in Figure 4, utilizes a rolling contact joint to manipulate the camera's position. This module comprises a backbone spring, two bending wires, and two wire guide springs. Additionally, the backbone spring is utilized for the cleansing motion to manipulate the module's head, where the camera is attached. A guide tube for the backbone spring facilitates this movement. The camera wire is threaded through the backbone spring, and the guide tube, composed of Teflon, minimizes friction between the spring and the tube during rotational and forward-backward movements.

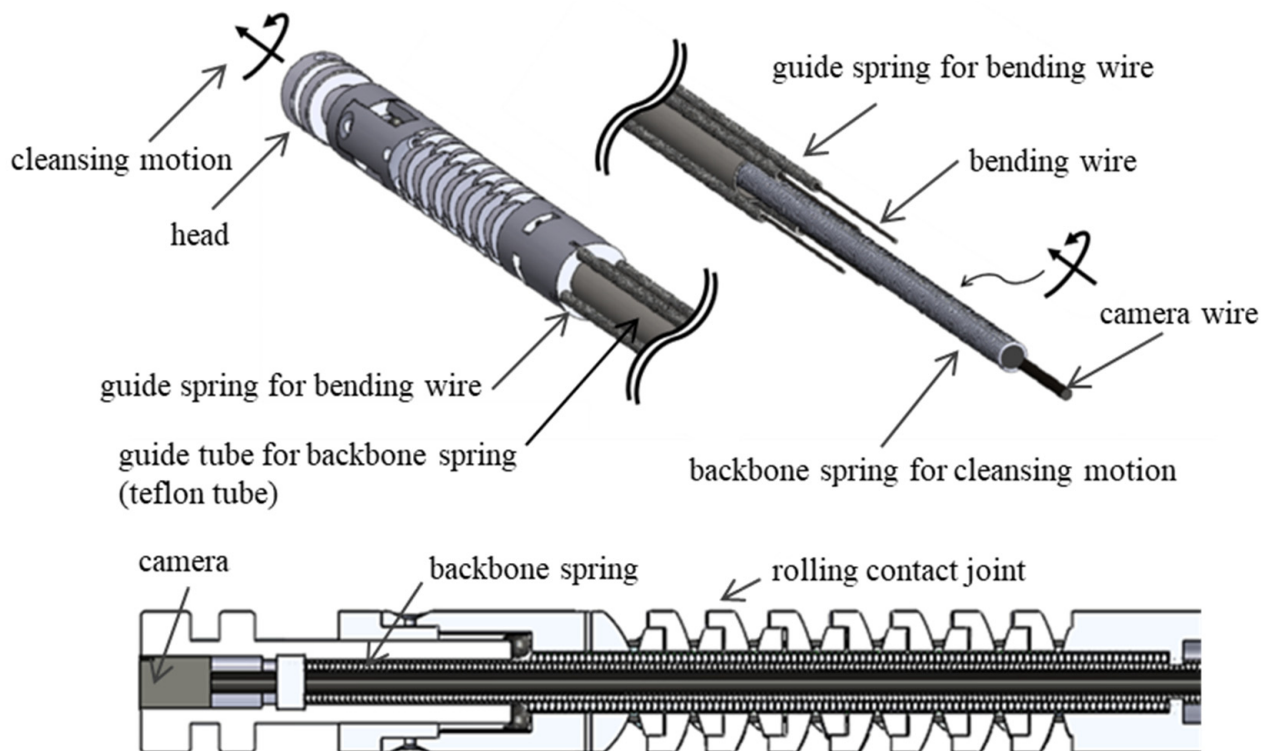


Figure 4. Design of the camera module. The camera module consists of a backbone spring, two pairs of wires, two pairs of wire guides, a spring for manipulating the head module, and a guide tube for guiding the manipulating spring. The two pairs of wires are used to control the vertical and horizontal positions of the camera, and the spring for manipulating the head module is used for the cleaning motion of the camera lens.

The IMU sensor (Figure 5) (Bno055, Bosch Corp., Stuttgart, Germany) integrated into the transmitter module's circuit continuously computes gyroscopic, acceleration, and geomagnetic values. These values are instantaneously converted into Euler angles, from which the yaw and pitch values are derived and transmitted to the microcontroller unit (MCU) (nrf52832, Nordic Semiconductor ASA Co., Trondheim, Norway) on the same circuit board via the two-wire interface (TWI) communication protocol. Subsequently, these values are relayed every 100 ms to the MCU (nrf52840, Nordic Semiconductor ASA Co.) on the receiver circuit board within the control module through wireless Bluetooth low energy (BLE) communication protocols. The receiver module translates these yaw and pitch values into corresponding angles based on the motor's positioning. The activation of the foot switch triggers an interrupt signal to the receiver's MCU, which, in turn, issues a universal asynchronous receiver/transmitter (UART) signal to the motor (XC330M288T, Robotics Co., Seoul, Republic of Korea). This motor is selected for its integrated driver-based MCU (Cortex-M0+ 32 bit, 64 MHz), which is optimized for its compact size. It employs a half-duplex asynchronous serial communication protocol utilizing a time-to-live (TTL) level multi-drop bus for simplified control. Furthermore, precise control is achievable by implementing a proportional integral–differential (PID) control algorithm. Including a contactless absolute 12-bit, 360° encoder (AS5601, ams-OSRAM, Premstaetten, Austria) facilitates precision control predicated on position, enabling the motor to operate according to the converted angle.

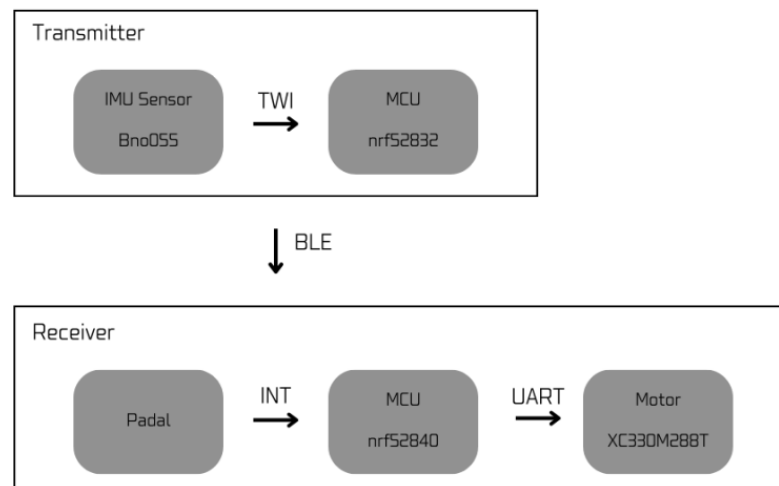


Figure 5. Firmware block diagram.

2.2. Development of a Trocar Specialized for ICT Laparoscopy Systems

The trocar (Figure 6), in conjunction with the ICT laparoscopy connector, enhances its utility by enabling the insertion of the camera drive unit into the human body, introducing structural improvements that minimize movement during surgical procedures and preventing the laparoscopy system from accidental dislodgement. At the trocar's upper segment, design enhancements were made to ensure stability and to deter the laparoscopy system from inadvertently exiting the body. Significant advancements in the design of the trocar's penetrating needle and obturator are instrumental in averting instability during the operation of ICT laparoscopy.

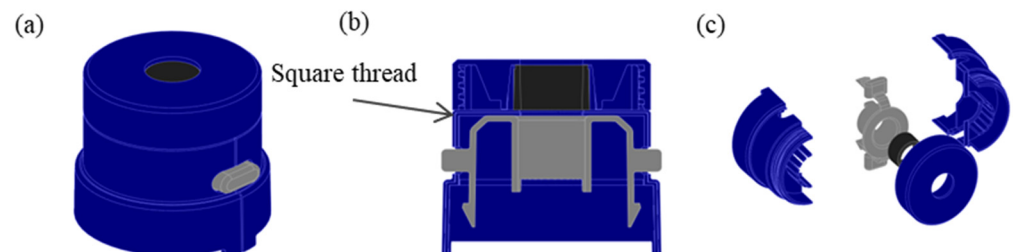


Figure 6. Structure of a trocar: (a) the finished product, (b) cross-section, and (c) product disassembly.

Moreover, stability was increased by introducing a square thread to avoid incomplete connection or loosening between the ICT laparoscopy and the trocar's upper clamping part. The trocar's overall length was purposefully shortened, relative to traditional models, to allow for the unobstructed rotation of the ICT laparoscopy system. Adopting the standard piercing needle, identical to those used in conventional trocars, eliminates the need for additional, specialized products for ICT laparoscopy, streamlining the surgical process.

2.3. Certified Performance Test of Main Body

In accordance with the requirements outlined in the Ministry of Food and Drug Safety Notification No. 2013-65, safety tests were conducted for specified items—leakage current, grounding resistance, and power input—under the General Requirements for Basic Safety of Medical Electrical Equipment, as stipulated in the IEC 60601-1 [23] series. These tests were executed by the Korea Testing Laboratory (KTL), where investigations aimed at measuring the accuracy, degrees of freedom, and range of motion for camera control based on controller values were also conducted.

The functionality of the ICT laparoscopy system was assessed in vitro using a laparoscopy phantom model (Laparoscopic simulator trainer, ICEN). Through this assess-

ment, the system's performance and the validity of its design were verified. The phantom model was equipped with rubber-packed holes for abdominal insertion, accommodating the dedicated trocar.

To emulate the clinical setting as closely as possible, a surgical doctor installed and evaluated the ICT laparoscopy system for its usability. This evaluation included considerations of the controller's weight and operational feel, the driving speed and range of the camera's movement, and additional clinical recommendations.

2.4. IACUC for Performance and Usability Test with Porcine

All animals were cared for following the guidelines of the Institutional Animal Care and Use Committee (IACUC # KMEDI-2372102-00). A surgical doctor conducted animal experiments on a porcine model, with the animals weighing approximately 40 to 45 kg. Induced anesthesia was achieved using Zolletil and Rumpun (Xylazine) through administered dosages of 5 and 2.3 mg/kg via intramuscular injection. General anesthesia was maintained through the inhalation of 2% isoflurane.

After the induction of anesthesia, the performance and usability of the camera insertion and intraperitoneal camera driving were evaluated. Performance assessment focused on the resolution of data recorded within the abdominal cavity and the wireless reaction speed between the controller and the camera. The usability evaluation considered factors such as the controller's weight, operating sensibility, driving speed, and the range of camera movements. The usability questionnaire was divided into four main categories: (1) operation and usability of the controller, (2) usability of the foot pedal switch, (3) delay time between the controller's action and the camera's motion, and (4) actuating speed and range of camera movement.

3. Results

3.1. Performance Test Results of Main Body

Figure 7 shows the prototype of the ICT laparoscopy system, engineered to mitigate the challenges previously outlined and facilitate solo surgery. This innovative prototype incorporates a hairband controller module that captures user motion in real time and transmits this information to the main unit when donned on the user's head. Additionally, it features a foot pedal switch for initiating the motion tracking of the head and a central unit responsible for transmitting and receiving data to regulate camera movement. The operation of the ICT laparoscopy system shown in Figure 7 is delineated in the following steps.

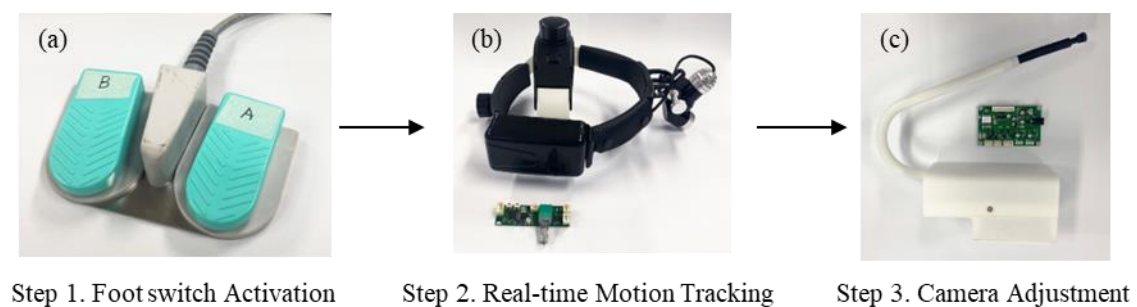


Figure 7. The operation procedure of the ICT laparoscopy system involves the following steps. First, (a) initiate the system by activating the foot switch (Step 1). (b) The user wears it on their head, and their head motion is tracked in real-time (Step 2). Next, (c) the camera is adjusted according to this motion (Step 3).

Step 1: The activation of the camera module is achieved by centering the camera and engaging the foot switch, setting the stage for the controller to commence motion tracking.

Step 2: Equipped with motion-tracking technology, the hairband controller responds to the user's head movements, enabling dynamic system control.

Step 3: By interpreting the user's motions, the hairband controller transmits a command signal to the camera, aligning the viewing perspective with the user's intent.

This operational flow highlights the ICT laparoscopy system's intuitive and efficient functionality. Safety tests, including leakage current, grounding resistance, and power input, were performed in alignment with the General Requirements for Basic Safety of Medical Electrical Equipment (IEC 60601-1 series) by KTL. These tests are crucial components of the General Requirements for the Basic Safety of Medical Electrical Equipment, ensuring the medical device's essential performance and basic safety in clinical settings. In the leakage current test, the leakage current of the device must be below the Ministry of Food and Drug Safety (MFDS) standards. In the grounding resistance test, for a device with a power socket, if the impedance between the protective grounding point of the power socket and grounded contactable metal parts does not exceed 0.1Ω , the test passes, and in this case, the test passed with 0.052Ω . The power input test is divided into devices that consume power by electric motors and other devices. This prototype belongs to devices other than those that consume power from electric motors. Hence, it is classified as another device. In the power input test of this prototype, the input current or power in the normal state under the rated voltage, normal operating temperature, and operating conditions set by the manufacturer must be less than 10% of the rated input exceeds 100 W or 100 VA, and this was satisfied (refer to Table 1). The prototype passed several safety tests for leakage current, grounding resistance, and power input. This achievement paves the way for further testing to ensure compliance with all requirements outlined in the General Requirements for Basic Safety of Medical Equipment in the future.

Table 1. Safety tests, including leakage current, grounding resistance, and power input, were performed in the IEC 60601-1 series by KTL. The leakage current test, conducted at a voltage of 264 Vac and a frequency of 60 Hz, differentiated normal conditions (NCs) and single fault conditions (SFCs). It passed tests within tolerance for the leakage current, grounding resistance, and power input.

Test Item		Acceptance Criteria		Result
Leakage Current	Earth Leakage Current	NC	0.5 mA	0.02 mA
		SFC	1 mA	0.007 mA
	Enclosure Leakage Current	NC	0.1 mA	0.28 mA
		SFC	0.5 mA	0.029 mA
	Patient Leakage	NC	0.1 mA	0.001 mA
		SFC	0.5 mA	0.001 mA
Grounding Resistance		0.1Ω		0.052Ω
Power Input		Input Current $\leq 10\%$	Rated Value	1.3 A
			Measured Value	0.15 A

Performance evaluations conducted by KTL-assessed dimensions and camera rotation angle. The main body dimensions were 192.86 mm in width, 192.58 mm in height, and 94.63 mm in depth. The camera showed degrees of freedom for movement in the up, down, left, and right directions, with rotation angles defined as 88° upward, 89.55° downward, 92.5° to the left, and 88.05° to the right, highlighting the system's versatility in camera motion control based on controller inputs.

3.2. Results of Performance and Usability Test Using Phantom Model

The performance and usability of the system were assessed using a laparoscopy phantom model. The actual response time between the controller's action and the camera's response was observed to be 3.02 ± 1.04 ms, on average, over 20 trials. Moreover, depending on the controller, camera movement was measured ten times for the up, down, left,

and right directions with averages of $90.05^\circ \pm 1.33^\circ$, $90.64^\circ \pm 1.31^\circ$, $89.87^\circ \pm 1.39^\circ$, and $90.41^\circ \pm 1.45^\circ$, respectively, and an accuracy of approximately 99.4%. Usability evaluations conducted by four clinical experts yielded the following results:

- (1) The average usability score for the controller was 90 points, with consensus among four surgeons;
- (2) The foot switch operation in the ICT laparoscopy system received an average score of 77.5 ± 3.75 ;
- (3) The average score for the operation and delay between the controller and camera was 81.25 ± 4.82 ;
- (4) The average score for the driving speed and camera range was 85 ± 5 .

This evaluative feedback was crucially utilized for product enhancement purposes. The dimensions and mass of the hairband controller were deemed suitable, and its operation method was also considered appropriate. The camera's rotation angle received a positive evaluation for its adequacy. However, there were instances where the movement perception was critiqued as overly broad, coarse, or rapid. This feedback indicates a need to enhance the smoothness and refinement of the camera movement. Users could benefit from customizable movement speeds to accommodate individual sensitivity variations, allowing them to adjust the speed according to their preferences.

3.3. Results of Performance and Usability Test with Porcine

A standard 15 mm trocar was utilized at the umbilicus to facilitate the smooth insertion of the prototype. Additionally, a 12 mm trocar was positioned, as indicated in Figure 7, to accommodate the insertion of a conventional laparoscope, enabling the observation of the prototype's movement. CO₂ gas was injected through the 15 mm trocar to establish pneumoperitoneum within the abdominal cavity (Figures 8 and 9).

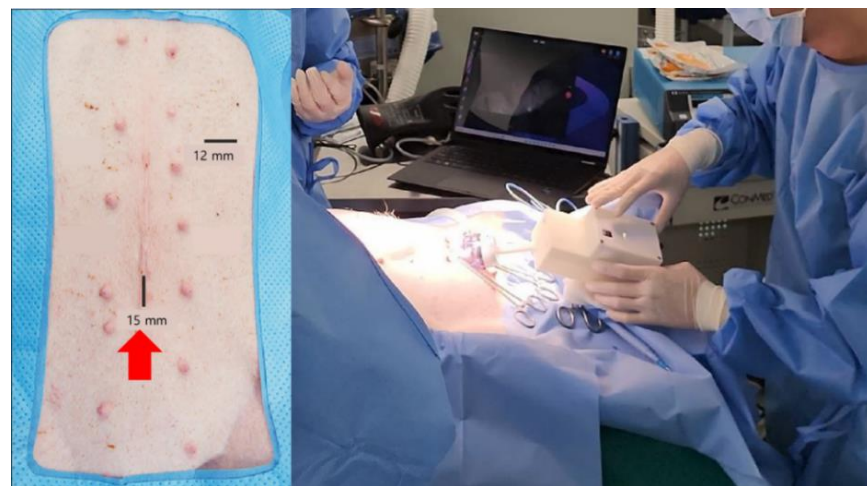


Figure 8. Trocar placements for the evaluation test of the ICT laparoscopy system prototype.

Utilizing the ICT laparoscopy system, tasks were executed in upward, downward, left, right, and diagonal directions, with data recorded within the abdominal cavity of a porcine model. Based on the surgeon's experience, these tasks facilitated evaluations of the system's operation, performance, and usability.

During the camera's movement, no interference or collision was observed with the abdominal wall, suggesting that the length of the laparoscopic camera was appropriate. Furthermore, the actual delay time between the controller's action and the camera's response was assessed to be within 100 ms. Despite this slight delay, it did not impede surgical operation significantly.

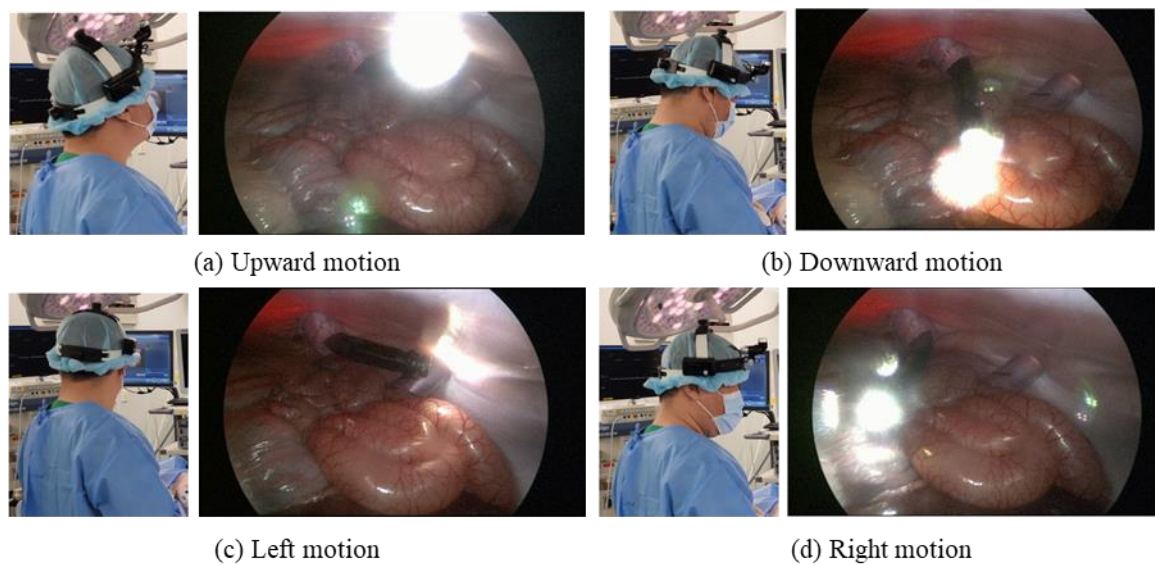


Figure 9. Captured pictures of the laparoscopic camera movements in the abdominal cavity prototype test. The direction of the camera switches according to the movement of the controller.

A comparative analysis of the recorded data revealed that our camera, with a 1 MP resolution, 720 p video quality, and a frame rate of 30 fps, possesses less than half the pixel count of traditional laparoscopes. Nevertheless, the camera provided satisfactory results regarding resolution and brightness—key factors for distinguishing organs and tissues during surgery. Additionally, compared with a common laparoscope, our prototype exhibited less lens fogging, a common issue due to temperature differences between the inside and outside of the abdominal cavity, regardless of the camera's position during the test.

Usability evaluations conducted by three clinical experts yielded the following results:

- (1) The average usability score for the controller was 85 ± 7 , indicating a high level of satisfaction with its operation;
- (2) The foot switch operation in the ICT laparoscopic system received an average score of 90 ± 10 , suggesting excellent usability;
- (3) The average score for the operation and the delay between the controller and the camera was 81 ± 6 , reflecting a minor concern regarding the response time;
- (4) The average score for the driving speed and range of the camera was 88 ± 10 , demonstrating a favorable evaluation of these aspects.

These scores collectively indicate a positive reception of the ICT laparoscopy system's usability and performance despite noted areas for potential improvement.

4. Conclusions

Comprehensive evaluation and testing of the ICT laparoscopy system showed that the prototype is promising for revolutionizing laparoscopic surgery. The system's intuitive interface and ability to integrate with surgical workflows seamlessly address key challenges surgeons face, particularly in the context of solo surgery and the anticipated exacerbation of the surgeon shortage.

The system's positive reception in usability and performance, demonstrated through tests on both phantom and porcine models and evaluations by clinical experts, highlights its potential to improve surgical outcomes while reducing technical challenges. Specifically, the system's accurate motion tracking is notable. There is minimal delay between controller action and camera response. Favorable evaluations of key critical functionalities, such as the foot switch operation and camera driving speed and range, also highlight its effectiveness in addressing critical needs in laparoscopic surgery.

Furthermore, some safety tests that complied with medical electrical equipment standards were completed to confirm performance and safety potential in a clinical environment.

In summary, our ICT laparoscopic system comprises a novel groundbreaking device that employs motion tracking of the surgeon for precise camera control, as evidenced by our latest prototype. Additionally, the ICT laparoscopic system contains an integrated camera-cleaning mechanism, which could further revolutionize surgical efficiency. This innovation streamlines the surgical process by eliminating the need for manual camera adjustments and cleaning, thereby facilitating solo surgery. These advancements hold great promise for enhancing surgeons' capabilities and optimizing surgical outcomes, ultimately benefiting patients. Future studies should prioritize refining system functionality, addressing areas for improvement, and conducting rigorous clinical trials to validate its efficacy in real-world surgical scenarios.

5. Discussion

The development of mechanical devices to assist surgeons in surgery has continued.

Robotic laparoscopic surgical instruments such as the Da Vinci and dexter robots provide users with a convenient and efficient surgical environment. However, there are still few significant benefits compared to conventional laparoscopic surgery, which has excellent operation time [16]. In addition, since the robot system is costly, an inexpensive laparoscopic holder that can be used in combination with conventional laparoscopic surgery must be developed [17].

Ethos' laparoscopic assistants were placed over the patient to maintain a free and comfortable posture from the surgical space, which substantially reduced the musculoskeletal pain of doctors. However, it increased the difficulty of most operations, and the chair's posture was evaluated as unsuitable for surgery. In addition, the study discussed the need to fix a laparoscopic camera [18].

The laparoscopic camera system using Senhance's gaze tracking supports better visualization—magnification, 3D images, and haptic feedback, and the platform is relatively cheaper than the Da Vinci system. However, this invades the surgical environment because it is expensive to purchase and maintain compared to laparoscopic holders and it is very bulky [19].

A voice-controlled robot-automated endoscopic system for optimal positioning (AESOP) is a voice-activated robotic scope holder (not commercially available). Because it is voice-operated, the instrument can be used with both hands, similar to the ICT laparoscopy system. Additionally, by remembering a specific position, the laparoscope can automatically return to that position. However, it takes up a lot of workspace and is expensive. Compared to the cart-type AESOP, the ICT laparoscopy system is compact and takes up less space [20].

The FreeHand[®] robot-assisted system operates in a form similar to the ICT laparoscopy developed in this study; hence, it does not require camera assistance. It does not occupy substantial surgical space, making it relatively inexpensive and suitable for solo surgery. In the operation of the FreeHand[®] robot-assisted system, the camera's head does not move, but because the rigid scope does move, the radius of movement is limited, and the space it occupies is relatively larger than that occupied by ICT laparoscopy [21,22].

Existing laparoscopy camera systems are predominantly designed with an elongated tube that houses objective and relay lenses [24]. However, significant efforts have been made to investigate the application of flexible laparoscopes in abdominal surgeries to address the spatial interference issues associated with the rigid lens tube of conventional laparoscopes [25]. Another challenge is the scarcity of trained scope operators capable of maneuvering the laparoscopic camera following the requirements of the surgical procedure and situation. The extensive training period for surgical assistants to become proficient has fueled the demand for automated assistive functions for laparoscopic camera adjustment and management within the surgical domain. Although mechanical camera holders and robotic arms have been developed and commercialized, their practical application in

surgeries has been limited due to the necessity of removing the tube from the body for lens cleaning.

The current development phase focused on the wireless adjustment of the camera actuator via motion tracking. Our study, based on the *in vivo* performance and usability tests with porcine subjects using the prototype of our ICT motion-tracking laparoscopic camera system, has demonstrated the system's feasibility for conducting laparoscopic surgeries efficiently and safely without requiring manual scope adjustment. Notably, the device eliminates the requirement to remove the scope during surgery. It incorporates a CMOS sensor that transforms visual information into electrical signals. This design is more cost-effective than traditional systems that rely on multiple optical lenses, facilitating the development of diverse and economical laparoscopic systems. Our objective was to ascertain the practicality of this conceptual idea in clinical settings. Equipped with wireless motion tracking, a wire-driven flexible tube, and a lens-cleaning mechanism that does not necessitate extraction, the system's mechanical performance and safety were rigorously tested in compliance with medical safety standards in anticipation of commercialization. Surgeons conducted usability evaluations, and the system underwent basic performance and safety verifications in a certified laboratory, including trials with phantom models and porcine experiments. A surgical expert reported a minimal delay of approximately 100 ms between user movements and the actuator's response, confirming the prototype's suitability for initial use. Despite the exceptionally low wireless transmission delay of motion data (below 1.3 ms), an increase in latency was observed when activating the motor and transmitting power via wire, highlighting the need for further latency reductions to ensure safe and effective operation.

As the development progresses toward commercialization, mechanical safety, durability, and waterproof validation require further attention. Although a basic waterproofing feature has been implemented, precise testing has yet to be conducted. Post-surgical sterilization is imperative for the system's continuous use; nonetheless, its durability, safety, and stability under various sterilization conditions remain to be fully established. Additionally, the scope's rotation angle improvements are necessary to enhance safety and stability within the human body. The current camera quality of 1 MP, 720 p, and 30 fps falls significantly short of the 4K (UHD) standard used in most surgeries, necessitating higher-performance camera components to achieve clinical applicability.

In response to the emerging trend of one-port robotic laparoscopic surgery, exemplified by the release of the Da Vinci SP system, we have developed a dedicated trocar with a dual structure to minimize interference between the camera and surgical instruments during laparoscopic surgery. The dedicated trocar facilitates the easy insertion of the camera module while securely positioning the main body. Despite advancements in precise one-port robotic surgery, conventional laparoscopic surgery will persist, owing to the variety of instruments required and the necessity for semi-precision surgery, especially for rapid procedures over extensive areas. Our cleaning technology, which does not require tube extraction, could enable true solo surgery.

Limitations such as video transmission via wire due to volume constraints are anticipated to be overcome with advancements in wireless communication technologies such as 6G, minimizing interference in operating rooms. However, establishing and implementing regulatory standards for the clinical application of these technologies is expected to be a protracted process. We aim to achieve video signal transmission with a delay of less than 20 ms, imperceptible to human senses, and to integrate a rechargeable battery to eliminate cable interference, ensuring the battery's capacity and durability meet surgical requirements.

Furthermore, the efficacy of an in-body camera lens-cleaning function has been substantiated. Prototypes equipped with a conventional type of laparoscopic camera demonstrated a reduction in lens fogging compared with traditional methods. It is posited that the use of non-metal materials in the camera module results in a diminished temperature disparity between the device's surface and the abdominal cavity, owing to differences in thermal

conductivity. Hence, employing non-metallic materials or materials with low thermal conductivity for the camera module to be inserted into the abdomen is deemed suitable.

AI could govern the fully developed version of our system during surgical operations, providing an in situ lens-cleaning function without removing the tube. The development of AI-based ICT laparoscopy systems will require deep learning algorithms trained on extensive datasets, including videos of camera movements for each step of the surgical protocol and situation, along with labeling to differentiate steps of the surgical process [26,27]. In particular, data pertaining to safety, specifically whether the camera lens can rotate and be cleaned without harming the patient, must be sufficiently collected [28].

AI cannot autonomously control laparoscopic cameras with the requisite safety and precision. As a result, surgeons are compelled to initiate motion tracking and control the camera actuator using a foot button, motion joysticks, or other sensing modules. Developing cleaning procedures that operate autonomously within the human body, without requiring surgeon intervention, represents an ideal advancement. The subsequent phase in AI system development necessitates the extensive accumulation and categorization of data into operational procedures and formulating the most effective algorithm through deep learning. Upon the stabilization of the AI system, laparoscopic surgeries will be conducted automatically within a safe parameter, based on surgical stages and situational voice commands, with manual adjustments being made by users only when necessary.

The development of a semi-automatic lens-cleaning function and a more practical two-joint activation structure for camera motion is required, as evident in the demands of surgeons. Furthermore, the miniaturization of the controller module fixed above the abdomen is necessary. Additionally, while the current system relies on wired video transmission, the transition to wireless transmission capable of supporting high-quality images over 4K at 64 fps remains a challenge to be addressed.

Author Contributions: J.-H.M. contributed to the study's conception and design. The Prototype was fabricated by M.J., H.L., S.K., S.L. and I.H. The animal study was planned by J.-H.M., J.-S.M., M.L. and M.-J.J., with participation from J.-S.M., M.-J.J., J.-H.M., M.J., S.L. and H.L. The first draft of the manuscript was written by M.L., J.O., T.K., S.L., M.J., M.-J.J., H.L., I.H., J.-H.M. and J.-S.M.; M.L., J.O., T.K., M.-J.J., S.K., J.-H.M. and J.-S.M. commented on the previous version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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