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Compact wireless laparoscopic device for single-port laparoscopic surgery

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ABSTRACT

Background: With visual data from laparoscopes, laparoscopic minimally invasive surgeries have several advantages over open surgeries. Usually, rigid endoscopes are preferred for laparoscopic procedures; however, rigidity limits organ access, and other devices or medical staff are often required to hold rigid endoscopes in place, hindering the surgeon's movement. Furthermore, the dissonance between the laparoscopic image and controls results in a steep learning curve for laparoscopy. Despite these limitations, few attempts have been made to design flexible laparoscopes that are easy to use.
Objective: To develop a flexible laparoscope that is self-immobilizing and spontaneous to use takes up minimal space, and causes minimal inconvenience to the surgeon's movement while maintaining acceptable flexibility.
Methods: We developed a compact, flexible laparoscope that can be controlled wirelessly. A wireless Android device receives visual data from the laparoscope over a local Wi-Fi connection; it displays images and enables control via buttons on an app. Motors actuate articulation of a backbone continuum structure in two dimensions and protrusion into the port. We evaluated the performance of the device in a laparoscopic phantom, the strength of the Wi-Fi connection, and the ease of cleaning.
Results: The flexible endoscope is compact compared with a conventional laparoscope holder. Simulation with a laparoscopic training phantom proved that the device could image the interior of the abdominal cavity while avoiding obstacles. The articulating ability helped the user to navigate various positions without the surgeon's relocation.
Conclusions: The device was helpful for simulated single-port laparoscopic surgery. With the device, fewer resources are needed for laparoscopic surgery, potentially promoting better accessibility of laparoscopic surgery and eventually leading to point-of-care laparoscopic surgery.

1. Introduction

Multiport laparoscopic techniques have revolutionized surgery [1]. Laparoscopic surgeries are performed more than 13 billion times a year globally [2]. With the aid of endoscopes and endoscopic surgical tools, the surgeon can access the desired tissues through minimally invasive wounds [3]. Single-port laparoscopic surgery pushes this one step further by putting a single port in a single wound that gives all required access to the interior of a body cavity [4]. Derivatives of single-port laparoscopic surgery, such as natural orifice transluminal endoscopic surgery and transluminal endoscopic surgery, obscure the wound further by utilizing the naturally generated ports, such as the belly button [5]. Multiport or single-port laparoscopic approaches are suitable for safe surgeries, provided the surgical needs are not too complex, and they are mostly used for uterine surgeries. In addition to being aesthetically pleasing, the minimal wound causes less tissue damage, assuring better and faster recovery. Single-port or multiport surgeries have lower mortality and reduced complexity [6–8].

Abdominal multi- or single-port surgeries have some shortcomings; however, they are an objectively better option than open-cavity

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surgeries. The biggest and most prominent problem of single-port surgeries is limited access. The endoscopes and endoscopic surgery tools are rigid; therefore, in abdominal cavities with many obstacles, the field of view and accessible field for the surgery tools are quite limited [9,10]. The collision between the surgical tools and endoscope often hinders the surgical procedure [11]. Surgeons usually overcome the limitation by switching the port to change the position, thus making the procedure tedious and unsafe. Conversely, limited access to single-port surgery can be partially overcome with a flexible endoscope, because the flexibility of the endoscope can cover the space covered by organs.

Another problem with single-port laparoscope surgery is the need for a separate endoscope assistant who holds the endoscope in place. In laparoscopic endoscopy surgery, the rigid endoscope that is usually used slides in and out of the trocar to give access to the abdominal cavity. However, since the endoscopes are heavy, and they can wander off in the tube of the trocar, the endoscope must be held at the desired position; otherwise, in the worst case, the endoscope can fall off inside the abdominal cavity, resulting in injuries in the organs. Usually, the surgeon uses one supporting personnel to hold and adjust the position of the endoscope. On the other hand, surgery robots can hold and adjust the position of the endoscope [12,13]. There are two drawbacks to surgical robot holder devices. First, the device only works as a holder; hence, the high price and huge dimensions of the device can seem unreasonable to many people. Furthermore, the holder can block the surgeon's hand or change position because of its massive volume and slow pace of movement, which can be critical in emergency surgery situations [14,15]. Because of these limitations, the learning curve of laparoscopic surgery is longer than that of open surgery [6,16].

To overcome the difficulties, several attempts have been made to amalgamate flexible endoscopes into laparoscopic surgery. A commercially available flexible laparoscope has a rigid body and flexible tip [17,18], and experimental attempts have been made to use flexible endoscopes the laparoscopes, sometimes complete with the motion compensation [19–21]. While flexible endoscopes have some limitations compared to rigid endoscopes, they have advantages over rigid endoscopes: flexible endoscopes have better maneuvering abilities than rigid endoscopes; hence, they have lesser chances of damaging the tissue [22]. Furthermore, they generally have better access to the target organ, since they have more accessibility to the body cavities [23]. Flexible endoscopes for diagnostic laparoscopy can access all the organs and intraperitoneal fluid inside the peritoneal cavity with a single trocar penetration. It is beneficial that flexible endoscopes are usually equipped with flexible surgical equipment [24]. Rigid endoscopes with flexible tips are beneficial in complex body cavities, such as the colon, or in pediatric patients with smaller cavities and organs compared with those in adults [25,26]. Flexible laparoscopic surgery has many advantages, and several other robotic devices have been developed; however, they are unsuitable for fine surgeries, unlike traditional rigid endoscope laparoscopic surgeries [27]. Nonetheless, flexible endoscopes are integrated into surgical tools. However, most surgical endoscopes for laparoscopy only have short, flexible parts. Furthermore, they still require holders and surgeons, just like rigid laparoscopic surgeries.

With the advantages of wireless devices, the flexible or rigid endoscope holders are implementing wireless control, which can reduce the contact between the controllers with the actual part that directly contacts with the patient's body. Mechanical controllers for the endoscopes are intuitive but have to be sterilized due to the contact and have a limitation of placement due to the length of the cables. Unlike mechanical controllers, wireless control enables the user to have freedom of movement and easier sterilization because light, wireless and smooth outside tablet devices can be used in place of the controller. Previous invention of a wireless mask endoscope could achieve less contact between the patient and operator to prevent transmitting highly contagious viruses. Furthermore, the freedom of movement from the wireless control can enhance the performance of the device handler. Moreover, the control can be done with a Wi-Fi connection; the device can be controlled over the network, enabling remote medical practices, such as remote surgery or endoscopic diagnoses.

To enhance the surgeon's experience, we developed a flexible endoscope with an articulable tip that can be controlled wirelessly while looking at the visual data from the endoscope.

2. Methods

We developed a compact, portable, and flexible articulable laparoscope and accompanying system for wireless visualization and control on a commodity tablet device. The laparoscope consists of a flexible endoscope probe with a continuum mechanism, a microprocessor for wireless control, four motors for continuum articulation, and one motor for winding the endoscope in and out of the endoscope body. The device is controlled by a smartphone application that complements the system, including a user interface based on directional buttons that grant the user control over the motors while streaming visual data back to the table in real time over a Wi-Fi network.

The portable contactless laparoscopic device is intended to be placed on the inflated abdomen of the patient, as shown in Fig. 1. The portable contactless laparoscopic device sends a stream of visual data to the Wi-Fi network while receiving the control signals from the mobile application over the Wi-Fi network. The tablet application receives and presents the visual data. The visual data can be adjusted and saved from the Android application. The process reduces the need for contact between the endoscope controller and surgeon; the endoscope can be controlled from the other side of the room or from outside if it is connected to the same network. The dimension of the final product is 175 mm (W) × 165 mm (D) × 180 mm (H). The inner connections in the device, consists of an endoscope module, LED, and wires relaying data and mechanical force (Fig. 2). The electric wires are connected to the raspberry pi, working as a controller.

The flexible part is spooled up in the device, ready to be rolled out or unwound from the device for insertion into a body cavity, as presented in Fig. 3. The endoscope tip slides out of a beak-like mount on one side of the device and can be inserted directly through a trocar, penetrating a port for laparoscopic surgery. The portable laparoscopic system is assembled as shown in Fig. 3(a). The flexible endoscope spooling mechanism is mounted upon a wide base. While the flexible endoscope can be broken down into a continuum unit and a flexible part, these are mounted on a disk that is rotated to insert the endoscope into the surgical field and held stationary to stabilize the endoscope. Pulleys built into the disk control the continuum unit actuation, transferring mechanical motion from the motors and keys to the wires that act as tendons in the continuum unit. The continuum unit, flexible part, continuum control wire pulley, flexible disc, and flexible disc case constitute a central "flexible module" on both sides laterally by the two motor modules. The motor modules consist of a motor disc case, motor disc, motor, and key, covered by a motor cover case.

The flexible part is articulated by a relay of force between several parts. First, the caterpillar connects the motor and motor disk pulley, and the motor disc pulley is connected to the flexible disc part. The assembled motor disc and flexible disc part rotate counter-clockwise to eject continuum and flexible parts from their rolled case. The motor pulley and continuum control wire pulley are assembled when the motor discs and flexible discs are assembled. The assembled continuum part is articulated by a coordinated motion of 4 motors and connected wires. This rotation and the components involved are presented in Fig. 4(a-d). For example, when the tip has to be articulated upward, the two left motors pull the wire-as displayed in Fig. 4(e), while the two right motors relax the wire. When the tip has to be articulated towards the left direction, the lower two motors pull wires while the upper two relax wires, as displayed in Fig. 4(f). The flexible part and continuum part combined, and the length of the part is 310 mm, including the camera at the tip and the length of the flexible parts. The flexible part should be rotated 273° to eject full length, as presented in Fig. 3(b). The weight of the flexible part

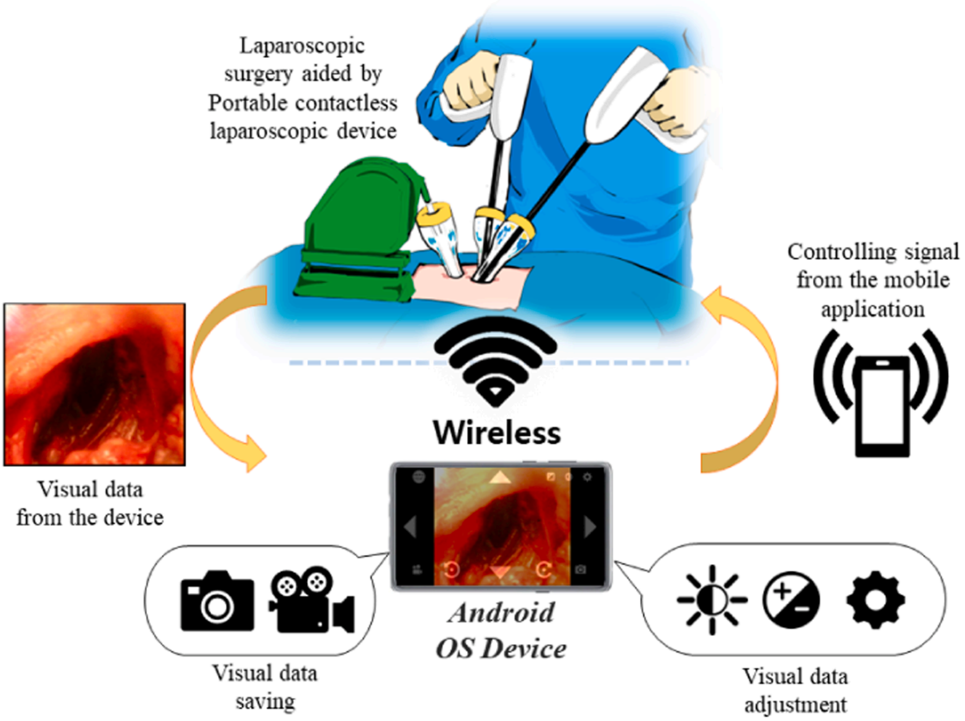

Fig. 1. Concept of new portable contactless flexible laparoscopic device and the associated wireless control systems.

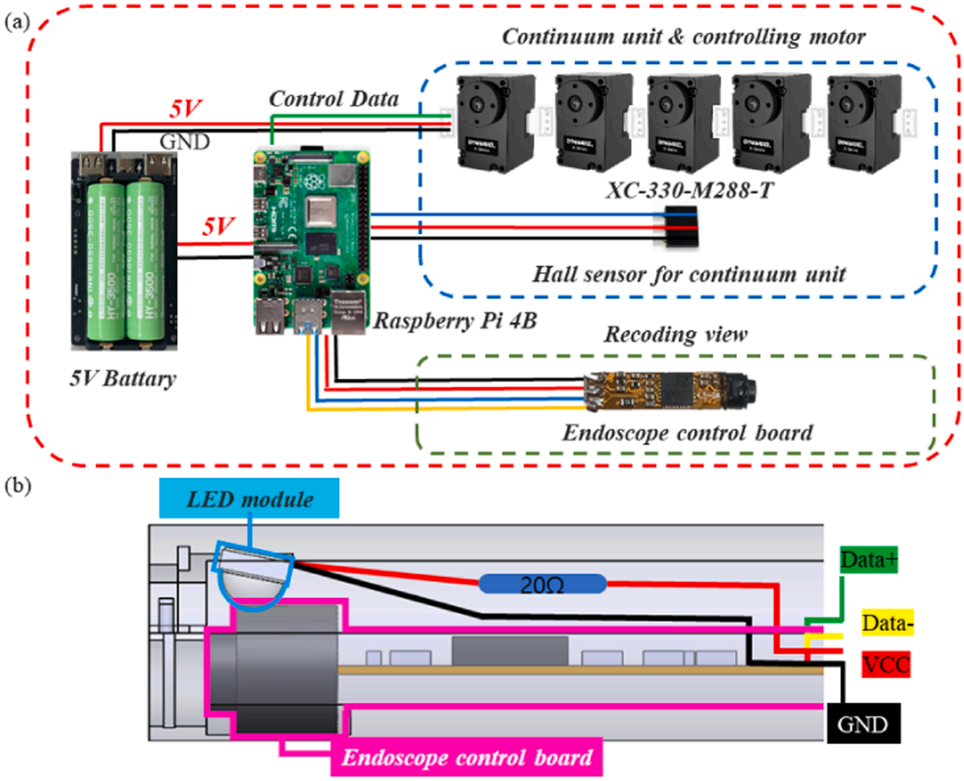

Fig. 2. Electric control diagram of the device systems. (a) The touch input from a smartphone application is captured via Wi-Fi and processed into motor control signals using a Raspbery Pi. The Raspberry Pi also processes video from the endoscope chip-on-tip module for transmission over local Wi-Fi. (b) The tip module of the endoscope comprises a chip-on-tip camera, an LED illumination module, and supporting electronics.

is 611 g in total, where 80 g of the flexible disc, 65 g of the motor disc, four motors with 23 g each, and others weighing 300 g. the outer diameter of the part is 140, which provides the required torque to rotate the device at 6110 g-cm; therefore, we chose Dynamic cell XC330–288 m-t for the motor. The motor is also capable of precise position control, enabling precise control even over long wire lengths by

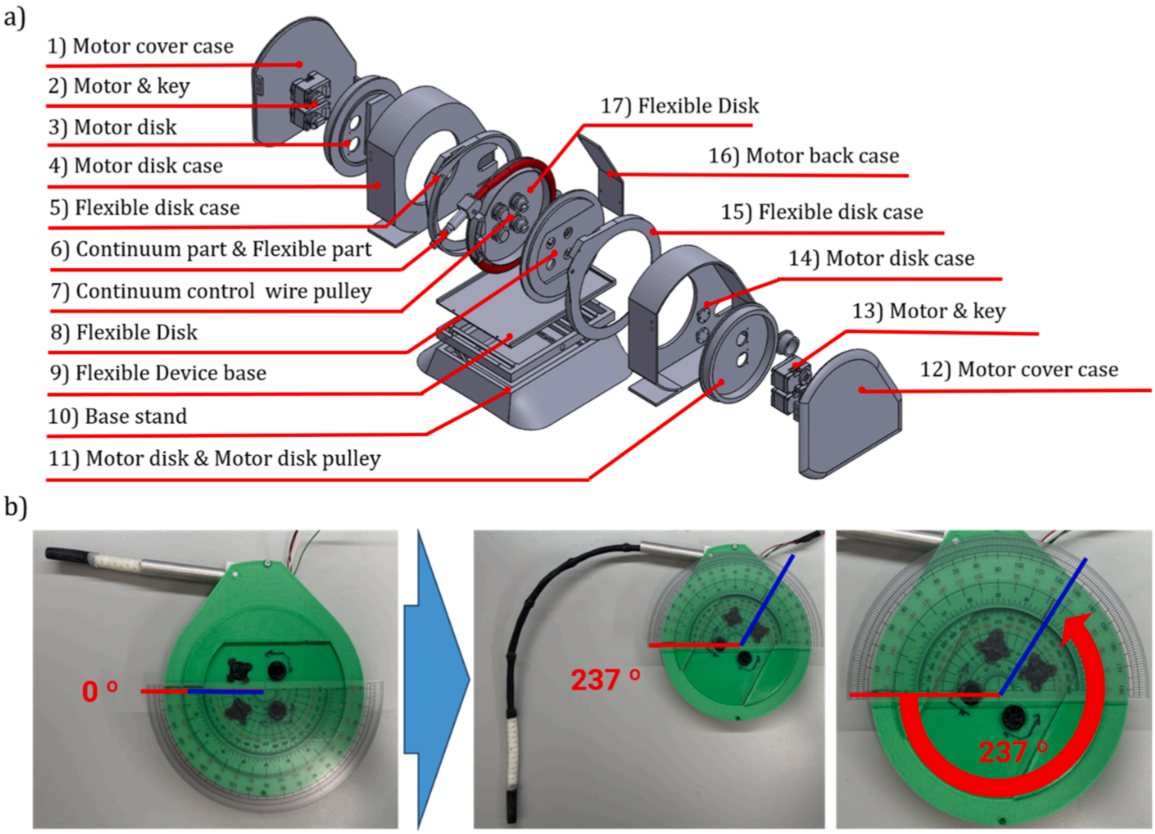

Fig. 3. Structure of the device. (a) Assembly of the portable laparoscopic device, with individual parts labeled. (b) Photo of the assembled fully functional device.

multi-turn mode embedded in the motor itself.

The endoscope mount module is designed to be separable to reduce contamination, thereby improving patient safety. However, to relay motor forces to the continuum unit, the spool disk must be somehow connected to the motor. To accomplish the relay of force, we adapted a key-and-pulley structure as described in Fig. 5. The key for each control wire is directly connected to the motor for that wire. It receives motor power to relay the force to the relevant continuum control wire pulley (Fig. 5(c)). The continuum control wire pulley has a wound side groove, controlling the wire that articulates the continuum part. In the center of the continuum control wire pulley lies a slot into which the key part can be inserted. By connecting the key with the slot, the rotation of the motor is relayed from the key to the pulley. Wire wound on the marginal groove of the pulley is either wound or unwound to control the continuum unit.

To support the movement of the continuum unit, allowing the whole flexible endoscope to be stored within, and to prevent the endoscope from collapsing because of gravity, the flexible part of the endoscope is covered with a shrinking sheath, as described in Fig. 6. Rigidity is added to the flexible part via aluminum rings (diameter: 6 mm, length: 4 mm) implanted in part at 50-mm intervals. The shrinking sheath is assembled by applying heat over the sheath surface, shrinking the sheath by 20%. This traps the aluminum ring inside the sheath, and the stretching of the sheath provides a tensile force that keeps the flexible part from collapsing. The aluminium ring's combined rigidity and the shrinking sheath's flexibility create a structure that aids the user in controlling the continuum unit. A small space is left between the aluminum ring and shrinking sheath to retain the flexibility of the flexible part. Therefore, the generated force affords more control of the continuum part according to the user's intent.

The shape of the small continuum unit pieces, the shape of the continuum unit joints, and their method of assembly are presented in Fig. 7. The endoscope's continuum unit is assembled as a chain of smaller identical continuum unit pieces. It is based heavily on the tendon-driven continuum idea [28,29]. The total length of the continuum unit is 58 mm. Holes in each piece of the continuum allow wires to go through to control the bending angle. To control the continuum with tendon wires, these four holes (each with a diameter of 0.5 mm) are inset on the rim of each piece. As presented in Fig. 7(c), continuum unit pieces were designed to bend 13° from the linear in two directions for a full articulation range of 26° per joint.

A single small continuum unit was designed based on the one-way joint to improve pre-existing tendon-driven continua. The planar articulation joint between pieces consists of prongs that protrude from each continuum unit piece and a joint guide in the subsequent piece. The joint guide reduces the twist of the continuum, which can be easily induced because of slight deformations at each joint between the small continuum pieces [30–33]. To reduce the friction between the joint guide and its corresponding prongs, the inner side of the corresponding parts, including the joint guide and prongs, has non-matching concave and convex shapes [34] (Fig. 7(b)). Inspired by the universal joint, each single continuum piece was placed with its direction turned 90° from the previous continuum piece [35].

The endoscope module at the tip of the endoscope has a camera unit (OV9734 package, TOLOS wire & electronics, 640 × 480 resolution at 30 fps and a light-emitting diode (LED) unit with 93.9 lm light intensity and 3 W power (Mouser Electronics, 941-XBDAWT000HBE7) for illumination of the imaged scene. The assembled continuum unit is hollow at the center, allowing electrical lines to run through for the endoscope module and LED light source. The attached LED has sufficient brightness for endoscopy since the light for the typical endoscopy uses around 100 lm intensity for the light source. Rechargeable batteries at the bottom of the unit supply electrical power for the endoscope and LED module.

A Raspberry Pi 4B (Raspberry Pi Foundation, UK) is used for the control unit. The built-in Wi-Fi support and computational power of a

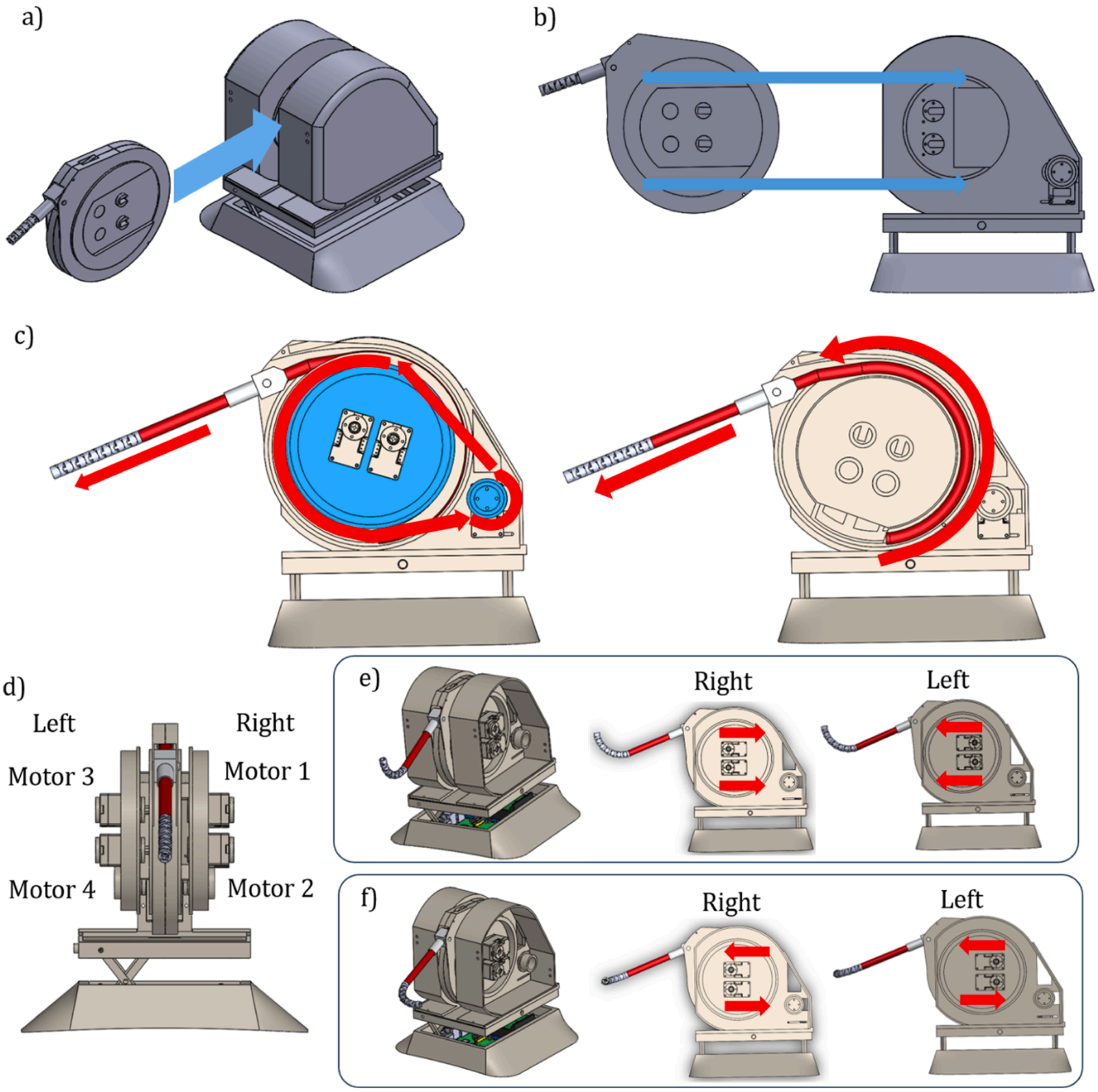

Fig. 4. Design and functionalities of the endoscope mount. (a, b) The endoscope assembly can be quickly removed from and inserted into the device for servicing and sterilization when the spool is in a horizontal position. (c) Rotation of the spool counter-clockwise (left) and clockwise (right) results in the flexible endoscope being inserted into or removed from the surgical field, respectively. (d) Front view of the design of assembled endoscope mount. (e, f) Motor motion according to the flexible part motion.

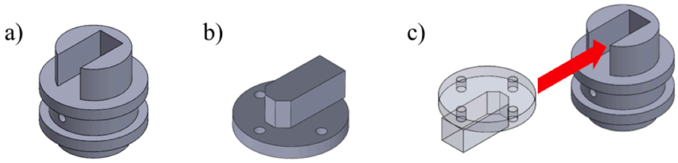

Fig. 5. Detail views of the keys and pulleys used for transferring force to the continuum wires while still allowing the wires to be replaced for servicing and sterilization. (a) 3D structure of the wire pulley. (b) 3D structure of the motor-mounted key which fits into the wire pulley. (c) Fit of the key into the wire pulley slot.

1.5 GHz Quad-Core Broadcom BCM2711 (Broadcom, CA, USA) [36] were sufficient for the unit to process and emit the video stream into the Wi-Fi network. An application was developed in Android Studio (Google, CA, USA) and written in Kotlin. The application is largely based on the previous wireless laryngoscope device of Moon *et al.* [37].

The user interface was designed to be suitable for use during surgery, with large buttons that are easy to touch, even with surgical gloves. The buttons are positioned to maximize both the area of visual data presentation and their intuitiveness (Fig. 8). Buttons for adjusting contrast and brightness adjust the properties of the image in real time. A setting button provides access to a Wi-Fi connection and resolution. Arrow buttons control motors that provide articulation. Furthermore, buttons for “roll in” and “roll out” control the endoscope spool, which winds the flexible portion of the endoscope in and out of the base.

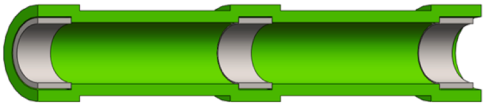

Fig. 6. Structure of the flexible part. The grey rings are aluminum rings for support, while green denotes a shrink-wrapped rubber sheath covering the outside of the flexible part.

The snapshot and capture buttons do not directly control the endoscope but set the tablet application to record the visual data received in

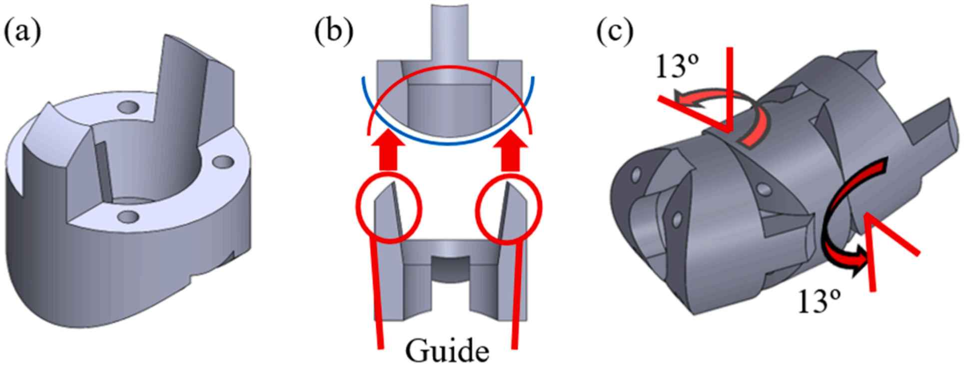

Fig. 7. 3D modeling and articulation of the small continuum unit. (a) A single piece of the continuum unit in perspective view. (b) Detailed structure of the continuum unit, showing how two pieces fit together. The two upward-facing prongs of the lower piece sit in a groove of the upper piece, as indicated by the red arrows. (c) The range of articulation between pieces in the small continuum unit is 13° front and back in a single dimension, with the direction of articulation rotating by 90° with every piece.

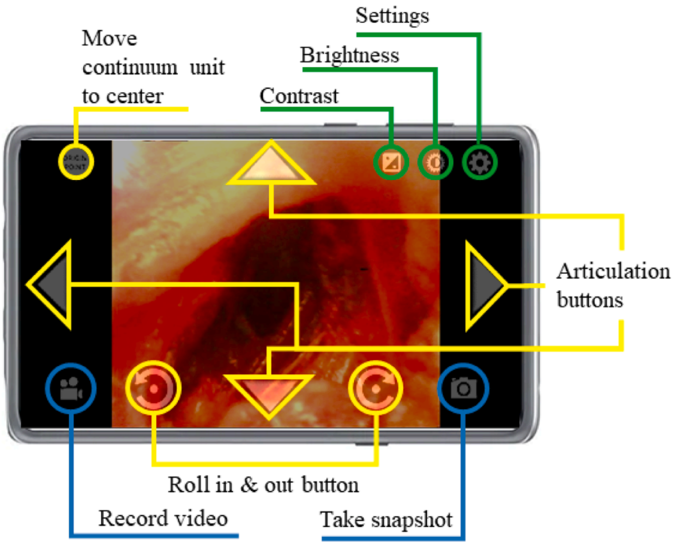

Fig. 8. User interface of the application.

predetermined formats. The application and device communicate with each other to facilitate the workflow (Fig. 9). Both devices are connected via Wi-Fi after bootup. After the connection is secured, the endoscope starts broadcasting the visual data to the application while the device listens for articulation commands from the application. Both the application and device can be shut down as the user desires.

3. Results

Three experiments were performed to evaluate the functionality and feasibility of the system. Wi-Fi controlled the device to measure the maximum laparoscopic bending angle and extent of endoscope insertion and winding, and the maximum possible articulations were commanded. After evaluating maneuvering ability, the device was used in a phantom surgery to test its practicality. The maneuvering ability of the device was evaluated for laparoscopic surgery when the captured images were saved using the smartphone application developed for the system. Finally, the workspace was evaluated between traditional laparoscopic surgery and laparoscopic surgery using the device to evaluate how the endoscope works in real surgery.

3.1. *Laparoscopic bending angle*

Conventional, rigid endoscopes use the 30°, 45°, and 75° angles of view, which is the angle between the endoscope body and tip plane. To enable the novel flexible endoscope to simulate the viewpoint and in-between angles, the inner software of the device is set to articulate the flexible part at 15° when the user pushes the articulating button in the application once. Furthermore, the maximum angle of the flexible part articulation is 90°, as demonstrated in Fig. 10.

To examine the maximum bending angle of the continuum component of the newly invented endoscope, the bending angle was measured for the maximum button press in the application. The maximum measured bending angle in each direction was ± 90°.

3.2. *Laparoscopic phantom surgery for real-life motion and imaging*

A phantom laparoscopic experiment was performed to measure the accuracy and articulating ability of the device. The device was tested on a human laparoscopic training simulator from IHEALTH (China). Blocks with different colors were placed in each direction inside the simulator. A GelPort Laparoscopic System (Applied Medical, Korea) simulates single-port laparoscopic surgery. A 3-cm incision was made on the belly button of the laparoscopic training simulator. The GelPort was installed into the incision, and an appropriate number of trocars were pierced through the GelPort. Surgical tools occupied two trocars, while one was reserved for the portable, flexible laparoscopic endoscope. The endoscope tip was inserted into the trocar, and as the model surgery started, the endoscope was connected to the Wi-Fi network, after which control was handed to the wireless Android tablet and its application.

The main target was set within the insertion range of the portable, flexible laparoscopic endoscope inside the laparoscopic training simulator. The position of the main target was 15 cm directly beneath the belly button. Peripheral targets were set at sites the tip of the endoscope can reach if it is articulated 45°. As shown in Fig. 11, the flexible part could maneuver the interior of the peritoneal cavity to obtain images of each target object. Endoscope insertion to a depth of approximately 10 cm and stable maintenance of insertion depth without the surgeon's intervention was demonstrated. The continuum endoscope was then articulated to aim at the four offset targets. In each case, the laparoscope could establish and maintain the desired position.

Fig. 11 shows images recorded via the application to evaluate the imaging capacity of the device. The image recording rate was 30 fps. Image focus depends on the proper insertion depth into the body cavity, and the field of view is limited by the 640 × 480-pixel output images (Fig. 11).

3.3. *Reduction of clutter and intuitiveness in the surgical field*

The space needed for the operation is simulated and evaluated by comparing it with the traditional rigid endoscope. The 45° rigid

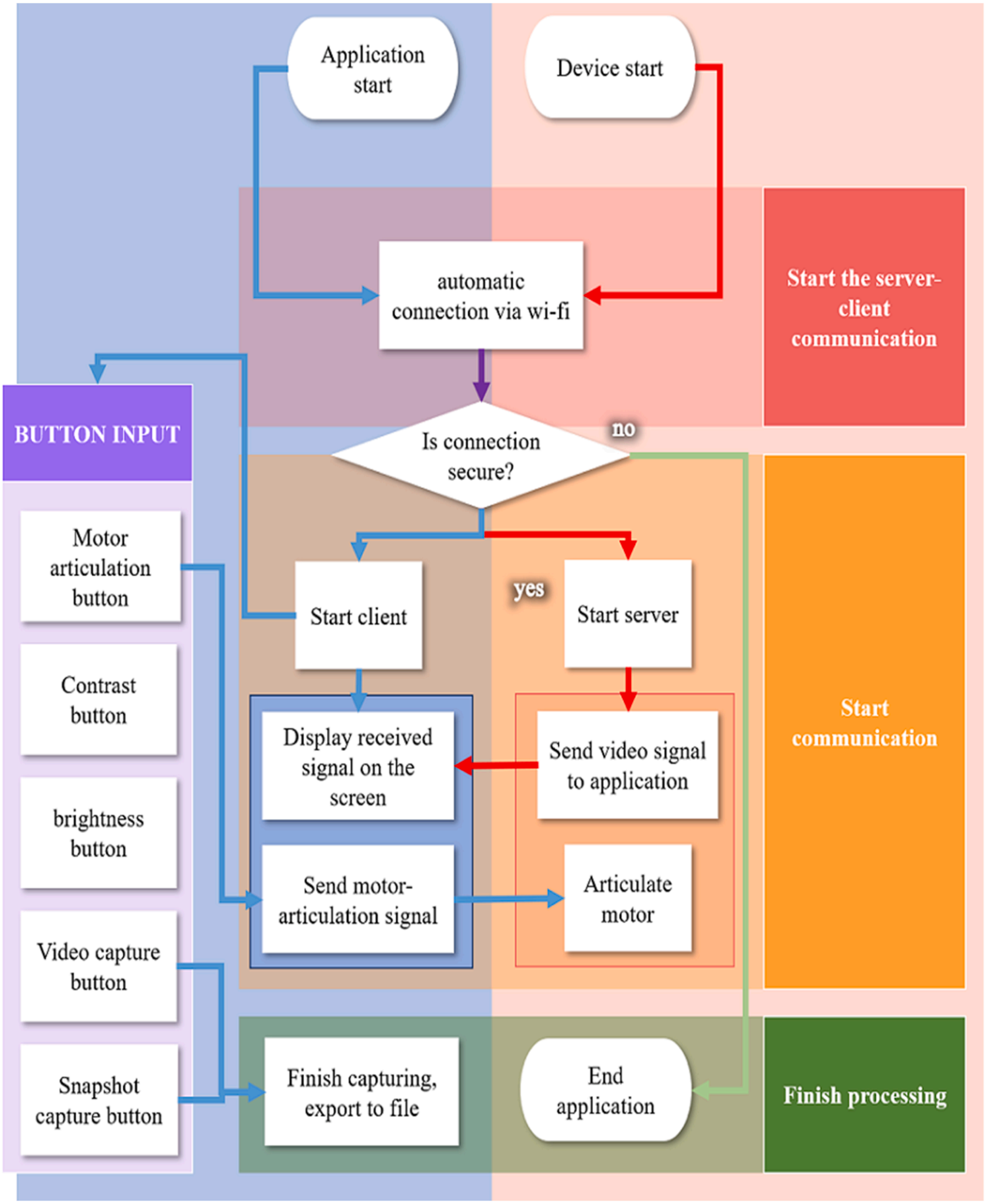

Fig. 9. Flow chart and workflow for the portable contactless laparoscopic device (right) and the tablet application used to control it (left).

endoscope and human laparoscopic training simulator from IHEALTH (China) were used as a testing ground, combined with the GelPort Laparoscopic System (Applied Medical, Korea). GelPort is installed in the laparoscopic training simulator, and each endoscope was installed in the Gelport with a trocar. A rigid endoscope was swung in four directions while installed to secure all the directions available. A novel laparoscope is put on the training simulator and articulated in four directions while it is installed to secure all available directions. The movement of the surgeon was assessed during the laparoscopic phantom surgery. The surgeon could look at the tablet in front of them, move freely around the phantom torso, and control the endoscope remotely. The surgeon required very little time to adapt to the device. Moreover, they could control the device to point at each target without noticeable delay.

4. Discussion

The novel device was capable of controlled articulation over wireless control and maneuvering within the simulated peritoneal 43and could capture all corners of the laparoscopic training simulator while presenting the visual data retrieved on the wirelessly connected tablet computer. With the maximum 90° articulation, we succeeded in emulating the visual capacity of a rigid endoscope, which has 30°, 45°, and 75° of angles of view, and succeeded in getting even more visual

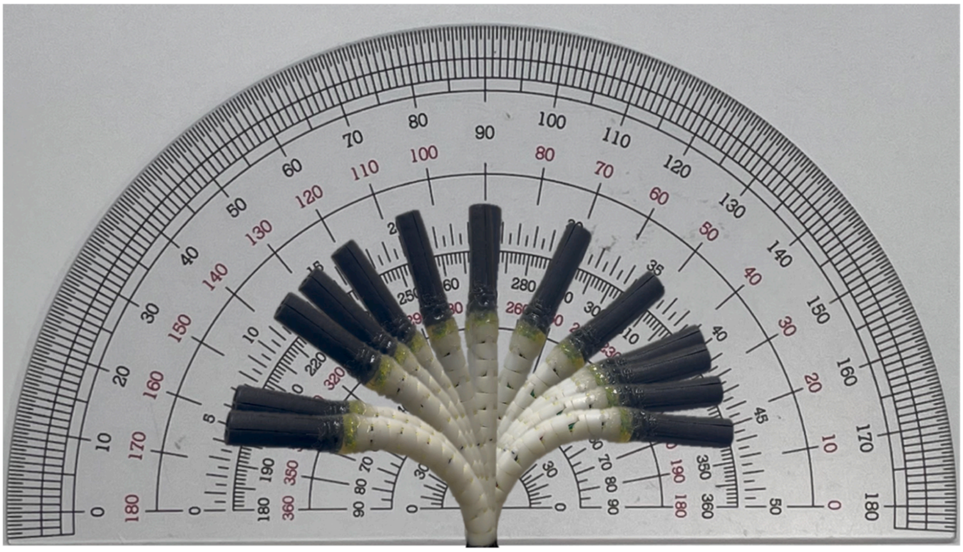

Fig. 10. Demonstration of the laparoscopic bending angle.

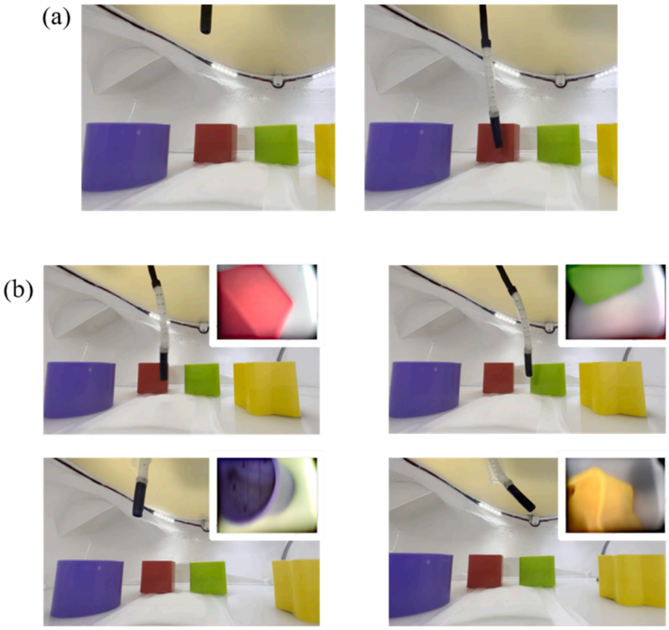

Fig. 11. Insertion (winding) and articulation of the flexible endoscope within a laparoscopic phantom. (a) Insertion range of the flexible part of the endoscope within the phantom (left) before insertion, and (right) after insertion. (b) The continuum endoscope as it articulates within the laparoscopic phantom to image different targets and (inset) images taken from each position.

freedom that is enabled by the maneuverability. Furthermore, it succeeded in retrieving a stream of 640 × 480 pixel images and broadcasting the data to the tablet system. The stream speed was 30 fps, sufficient for recognizing regions of interest in the peritoneal cavities [38,39]. A 93.9 lm light intensity of the LED module was also sufficient for the laparoscopic surgery since the intensity of the light needed for the laparoscopy is around 100 lm [40,41].

The standard procedure for laparoscopic surgery is summarized as follows: first, the abdominal cavity was inflated with gaseous CO_2. Small incisions were made, and trocars were inserted to secure the opening to the cavity before inserting endoscopes and surgical devices through the trocar. Finally, the surgical procedure was performed [40]. During the surgery, the equipment was moved manually according to the surgeon's needs. The process usually requires an extra individual or a holder robot [41,42]. The commercial price of a holder robot is over 80,000 US dollars, while its physical dimensions are similar to a person standing, making it bulky and expensive [43–45]. The size of the novel laparoscope was 175 mm (W)* 165 mm (D)* 180 mm (H), which is much smaller than the traditional endoscope holder. Furthermore, device articulation enables steering of the continuum part of the endoscope. The articulable device reduces the need for a surgeon to maneuver the viewpoint; it can also reach sites that rigid endoscopes cannot. Without the obstruction caused by wires or metal rods, surgeons can move relatively freely compared to traditional laparoscopic surgical procedures. If an assistant is needed to hold the Android device, the assistant can cast the visual data gathered from the device to a larger screen, such as a mounted television.

An intuitive design for laparoscopic endoscopes has been a concern for surgeons as they must watch the monitor instead of the surgical tools they are operating. A few attempts have been made to integrate wireless visuals into the surgical tool to lessen the dissonance between the eye and hand operation [43]. A laparoscope holder controlled by voice commands was proposed to intuitively control a rigid laparoscope. However, voice control was discarded because of its potential for malfunction and the need for a separate voice card for every individual who operates the machine [19]. Unlike the previous wireless laparoscope, the novel device allows the visual field to be freely moved and fixed at the user's discretion, with near-instantaneous camera feedback. The surgeon can move both the endoscope tip and visual display device. The intuitiveness of the user interface reduces the surgeon's spatial disorientation and helps the surgeon locate and perform the surgery in the appropriate space. Laparoscopic surgeries have a steep learning curve due to their limited field of view and non-intuitiveness. The steepness of the learning curve has reduced medical staff participation in laparoscopic surgery, thereby making surgery more difficult. With intuitive surgery, the learning curve of laparoscopic surgeries can be reduced, potentially resulting in better surgical performance.

The device uses a key and continuum structure controlled by wires and pulleys, which relays the rotatory torque of four electric motors through the flexible endoscope and the continuum part of the endoscope, thereby powering the articulation. We used such a design to make the continuum module removable. Laparoscopic procedures require direct contact between the open wound and laparoscope. Since the continuum and flexible parts directly contact the patient's body and body fluids, they must be considered contaminated after a single use. Sterilization is, therefore, necessary if these parts are to be reused;

otherwise, they can become vectors of infectious diseases. Several other laparoscopic and surgical devices use coverings, such as the Endosheath® to prevent contamination [44,45]; however, the device must be sterilized after several uses. With the interchangeable continuum module, we can first introduce a vinyl drape between the key and continuum control wire pulley to prevent contamination of the motor module. Users can then discard and exchange the continuum module, thereby creating safe and sterile devices for surgery.

The device is small and light; therefore, it can be moved to different spaces with little to no effort. This feature can reduce the number of devices needed for facilities by transporting the device quickly to the other sides of the facilities or reduce the resources needed for transportation to the desired location by being smaller and much lighter. By reducing the number of massive, expensive devices, the proposed laparoscopic device can reduce the overall cost and complexity of surgical procedures, thereby increasing accessibility for those in need.

The wireless control feature of the device could successfully reduce the personnel needed in the surgery room since the device can be controlled from another space. The separation between the control and the device can achieve two things: one, with fewer people in the room, more free space is secured for the operating person to move around, and two, lesser contact between the device and the hand can ensure sterile procedure and prevention of the splash caused by surgical procedure. Moreover, remote operation of this device and similar devices may also enable future point-of-care laparoscopic surgeries. Since the device is connected to the application via a Wi-Fi network, theoretically, it can be controlled on the other side of the globe if connected to the same network. Thus, the device can be used if there is a lack of room to get the person in the field surgery or if the person who operates can be separated from the patient. For example, in a disaster rescue operation, when the patient is in a small space they can't get out of, the device can get in and do the job while being controlled outside the tight space.

The design of the device is limited by a few physical constraints. The length of the articulating unit is limited to 8 cm; the available length of the flexible part in a flexible endoscope is shorter than 40 mm [46]. This problem is yet to be solved for many articulating commercial endoscopes. Images of 30 fps and 640 pixels are sufficient for medical diagnosis; however, users can obtain better surgery results with better image quality. The articulating ability and the image quality can be improved by increasing the diameter and changing the principle by which the continuum is articulated. Despite the size and portability limitations, the device reduces the resources needed for laparoscopic surgery while expanding the possibility with the portability and wider range of the view.

To summarize, the device was designed with portability and wireless operation, which can enhance the surgical procedure with no-contact operation, and small dimensions, which do not disturb the surgical procedure.

5. Conclusions

We have introduced a novel, flexible laparoscope for single-port laparoscopy, which can be controlled via a smartphone over a Wi-Fi network. The device demonstrates 90° articulation via a multi-backbone continuum structure and can maintain its position in a tissue port without human assistance. It has been demonstrated to be effective for capturing images and performing remote operation in a laparoscopic phantom, with the endoscope module having a footprint of 20 cm × 20 cm and weighing 1 kg. Future iterations of this class of device may reduce costs for greater accessibility, reduce the device weight and cost, and improve sterilizability for demonstration in the clinic. Furthermore, the device promises to free up surgical assistants for other tasks, streamlining the theater and increasing accessibility to lifesaving medical care.

CRediT authorship contribution statement

Choi Jaesoon: Funding acquisition, Resources, Supervision, Validation. **Namgoong Jung-Man:** Funding acquisition, Resources, Supervision, Validation, Writing – review & editing. **Oh Jeongmin:** Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Hyun Jaeho:** Data curation, Investigation, Methodology, Resources, Software, Validation. **Lee Kwanhee:** Data curation, Investigation, Methodology, Resources, Software, Visualization, Validation. **Kim Youngkyu:** Data curation, Methodology, Software, Visualization. **Kim Jun Ki:** Conceptualization, Funding acquisition, Investigation, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Moon Youngjin:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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