A Sigmoid-Colon-Straightening Soft Actuator With Peristaltic Motion for Colonoscopy Insertion Assistance: Easycolon

Hansoul Kim, Joonhwan Kim, Jae Min You, Seung Woo Lee, Ki-Uk Kyung, and Dong-Soo Kwon

***Abstract*—A colonoscopy is the most typical method to inspect for colorectal cancer; however, inserting colonoscopes in nonfixed sites, such as the sigmoid colon, requires very skilled insertion techniques. Since the sigmoid colon is one of the most difficult nonfixed sites for insertion, straightening it is a major step in colonoscopy. Previous studies have proposed various methods to assist the colonoscopy insertion process, but there are still challenges that must be addressed in clinical environments. The goal of this study was to assist colonoscopy operators to straighten the sigmoid colon using peristaltic motions generated with a soft actuator mounted on a commercial colonoscope. The peristaltic motions of the proposed system were combined with expanding and extending behaviors, and the straightening strategy was defined based on the analysis of the sigmoid colon handling process of colonoscopy. The peristaltic motions of the soft actuator were implemented using two balloons and a tendon-sheath mechanism. The colon shortening speed was measured to be about 80 mm/min, which contributed to the straightening of the sigmoid colon, thereby helping significantly with the process of colonoscopy.**

***Index Terms*—Colonoscopy, sigmoid-colon straightening, peristaltic motion, soft actuator.**

I. Introduction

COLORECTAL cancer is the third-most type of common cancer worldwide [1]. As more than 80% of polyps progress to colorectal cancer over 5 to 10 years through the process of carcinogenesis, the occurrence of colorectal cancer can be reduced by finding and removing precancerous lesions, such as polyps. In addition, early detection and treatment are very important because the survival rates vary greatly depending on the progression of cancer [2].

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A colonoscopy is the most typical method of inspection for colorectal cancer, and it also allows the treatment of lesions through surgical procedures using surgical tools [2]–[5]. The ideal colonoscopy reduces the patient's pain and enables examination within a short time [6], [7]. For a successful examination, a colonoscope should be inserted appropriately by accounting for the characteristics of the various parts of the colon. The large intestine is mainly divided into fixed and nonfixed sites; the sigmoid and transverse colon are nonfixed sites in the large intestine. Since the nonfixed sites move according to the movements of the colonoscope, the difficulty of insertion is higher in the nonfixed sites than in the fixed sites. Failure of appropriate insertion could cause pain and increase the risk of complications from loop formation in the colon [8]. In addition, since insertion in the sigmoid colon is the most difficult among the nonfixed sites [9], successful insertion is key to the colonoscopy process. To successfully insert the scope in nonfixed sites in the colon, skilled insertion techniques are required to straighten the colon. Since these techniques have a broad learning curve, novice colonoscopists require a long time to master the necessary skills. This also poses a physical and mental burden on sufficiently experienced colonoscopists to perform the procedure several times a day [9]–[11]. Therefore, there is a need for a safe and efficient method that can assist in colonoscope insertion.

Unlike the push-type commercial colonoscopes, endoscopic robots are capable of self-propulsion via various methods [12]–[17]. Prendergast *et al.* proposed a teleoperated endoscopic robot consisting of several wheels, timing belts, and DC motors [12]. Nagase *et al.* proposed a mechanism capable of propulsion by attaching several crawler belts to a flexible shaft [13]. Endoscopic robots that simulate the locomotion of the inchworm or earthworm using various actuators have also been proposed [14]–[17]. Lee *et al.* simulated the locomotion of an inchworm using shape-memory-alloy springs and silicone bellows and supplied power with an electric cable [14]. Chen *et al.* implemented inchworm-like propulsion using two linear and four twisted balloons [15]. Manfredi *et al.* used two balloons and a 3-degree-of-freedom (DOF) soft pneumatic actuator to simulate the locomotion of the inchworm [16]. Nakamura *et al.* proposed a propulsion method using peristaltic motions to simulate an earthworm with the McKibben artificial muscle [17]. Additionally, unlike the self-propulsion method that uses various actuators, a small-capsule endoscope robot that can diagnose

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internal lesions via peristaltic motions and the gravity of the digestive organs has also been proposed [18], [19].

Although various preliminary studies have been proposed on appropriate insertion techniques, there are still challenges that need to be overcome before any of these methods can be applied to clinical environments. With the exception of an endoscopy camera, it is not clinically appropriate to use electric actuators inside the human body [12], [14]. Since the mechanisms for self-propulsion are difficult to secure on the surgical tools or service channels inside the robot, surgical procedures, such as lesion therapy, are limited [13]–[16]. The air pressure used to actuate the mechanism also poses clinical problems as it exceeds the allowable pressure in the large intestine [17], [21]. Capsule endoscope robots are limited by the fact that it is difficult for them to perform tasks other than diagnoses through a camera [18], [19]. Therefore, there is a need for a method that can assist with colonoscopy insertion, performing surgical procedures, and clinical use.

In this study, we propose a colonoscopy-assistance soft actuator that can be mounted on a colonoscope to straighten the sigmoid colon. The proposed method can solve difficulties associated with colonoscope insertion by straightening the sigmoid colon using peristaltic motions aided by two hollow-type balloons. Since the proposed system can be mounted on a commercial colonoscope, the surgical tool and service channels can be secured. Considering the minimization of clinical problems, the required behaviors of the proposed system were decoupled for the balloons and tendon-sheath mechanism (TSM), such that the proposed system could be controlled within the allowable pressure range in the colon. Therefore, the system can be applied to clinical environments and used not only for diagnosis but also for surgical procedures.

The remainder of this paper is organized as follows: Section 2 describes the design and fabrication process of the proposed system. The straightening strategy is defined in Section 3 by analyzing the behaviors of the sigmoid colon. Section 4 describes the user-test design and results to validate the proposed system. The discussion and conclusions of this study and an outline for further work are described in Sections 5 and 6.

II. Development of Sigmoid-Colon-Straightening Soft Actuator: EasyColon

A. Mechanical Design and System Architecture

The overall mechanical structure of the proposed system comprises a fixed part, six tension springs, and two balloons, as shown in Fig. 1(a). The initial diameter and length of the proposed system are 26 mm and 90 mm, respectively.

The proposed system should be able to perform colon shortening through a straightening strategy, as described from the experimental results in Section 3, and be mounted on a commercial colonoscope to secure both the surgical tools and service channels. The colon shortening behavior was implemented by simulating the peristaltic motions of earthworms. These motions were combined with expanding and extending behaviors, as shown in Fig. 1(b). The inner wall of the colon was anchored through the expanding behavior, and the colon was shortened through

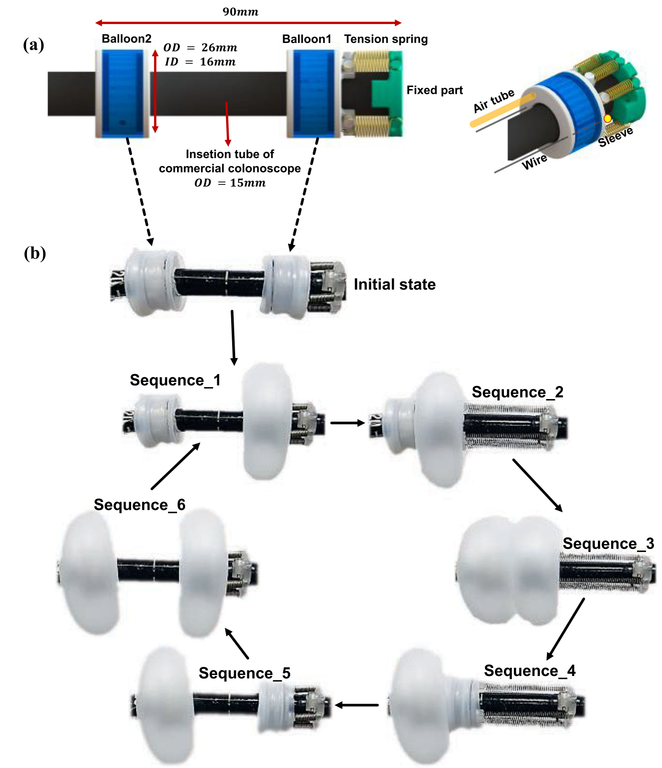

Fig. 1. (a) Overall mechanical structure of the proposed system and (b) peristaltic motion for colon shortening.

the extending behavior. The proposed system was mounted on a commercial colonoscope via its hollow-shaped design. The sus wire and sheath used for the extending behavior and the air tube used for the expanding behavior are arranged as shown in Fig. 1(a).

To minimize damage to the inner wall of the colon and clinical problems when using the proposed system, the expanding behavior was implemented using balloons made of biocompatible silicone (Eco-Flex00-30, Smooth-On Inc.) and controlled by pneumatics [20]; balloon 1 is movable and balloon 2 is fixed on the colonoscope.

In consideration of the miniaturization of the overall size of the proposed system and ease of control, the extending behavior was implemented using the TSM and tension springs. Since the TSM can only exert force in the pulling direction, tension springs help balloon1 return to its initial position after the extending behavior. The stroke, stiffness, and initial tension of the tension springs were 40 mm, 0.018 N/mm, and 0.049 N, respectively.

The overall scheme for controlling the proposed system is as shown in Fig. 2. Each pneumatic part for controlling the two balloons is used for the expanding behavior, and the motor driving part for controlling the TSM is used for the extending behavior.

The pneumatic part consists of an air compressor (JOLLY, NUAIR), 5/3-way solenoid valves (SY3320-6LZ-M5, SMC Pneumatics), air-pressure sensors, a relay switch, speed controllers, and an I/O board (Phidget Interface Kit 8/8/8 1018_2, Phidgets). The air compressor's built-in regulator and speed

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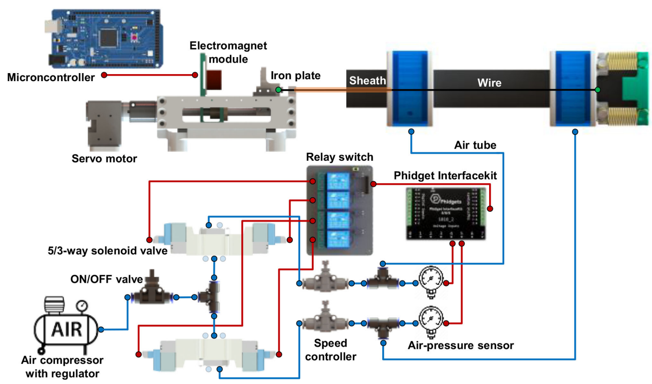

Fig. 2. Overview of the system architecture.

controllers were used to adjust the input pneumatic pressures to within the operating pressure ranges of the 5/3-way solenoid valve and balloon. The inner wall of the colon was anchored by holding the air inside the balloon using the 5/3-way solenoid valve. The air-pressure sensor was used to not only prevent the balloon from exceeding its allowable pressure when expanding but also compensate for any abnormal pressure decrease when holding.

The motor driving part consists of a servomotor (Dynamixel XM-430-W210-R, ROBOTIS), electromagnet modules (CT008617E, Crowtail), and a microcontroller (ARDUINO MEGA 2560). A lead screw and linear guide were used to implement the linear extending behavior using a rotation servo motor. The electromagnet module was selected by considering that the maximum pulling force of the colonoscope in the clinical sigmoid-colon handling process was 10.48 N. The electromagnet module was used to improve the return velocity of balloon1 after extension using the reaction forces of the tension springs.

B. Fabrication of Balloon

The overall fabrication process of the balloon can be defined in five steps, as shown in Fig. 3. A total of three molds were used: molds A, B, and C. All the molds were made of aluminum metal. First, a release agent (ER-200, Smooth-On Inc) was sprayed on all the molds to enable easy removal of the silicone from the mold. After assembling the three molds, silicone that was mixed and sufficiently defoamed was poured into the assembled molds. After curing for 30 min at room temperature and 30 min at about 100 °C using an oven, the cured silicone was removed from the assembled mold and placed on each rigid part of the balloon. After inserting an air tube into each of the air channels of the rigid parts, the silicone and rigid parts were restrained using threads, and sufficient restraint is ensured to prevent air leakage. Finally, a silicone adhesive (Sil-Poxy, Smooth-On Inc) was used to prevent air leakage between the silicone and rigid part.

C. System Validation

The colon shortening performance of the proposed system based on peristaltic motion was verified by straight-colon

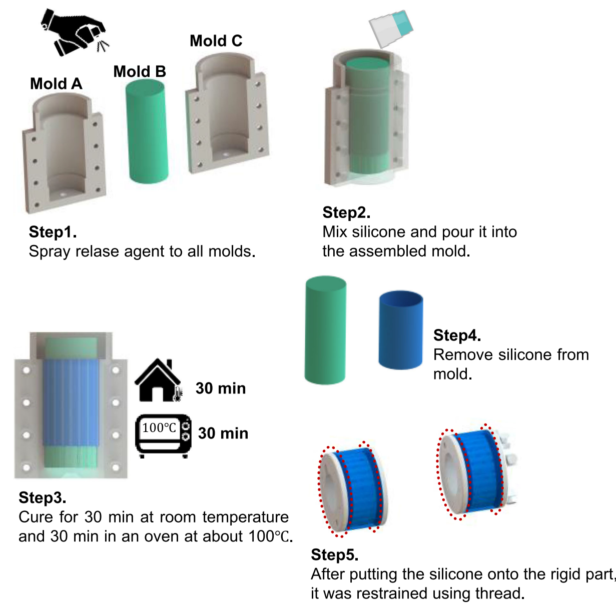

Fig. 3. Fabrication process of the two balloons.

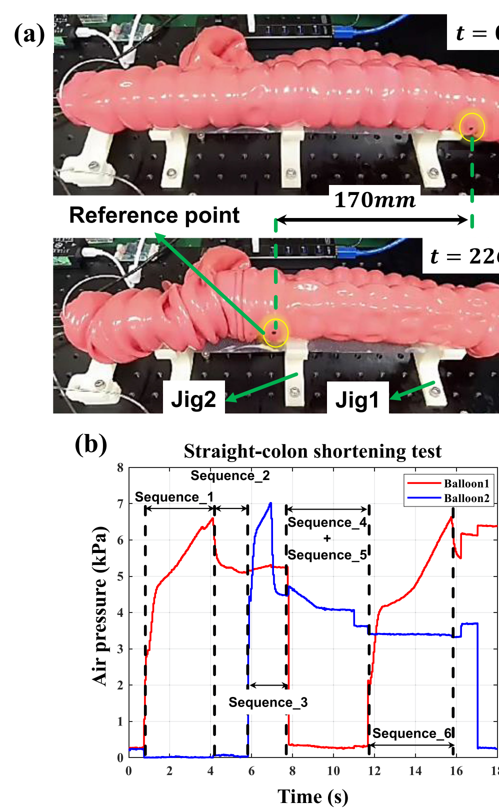

Fig. 4. (a) Before and after shortening in a straight colon and (b) air pressures of the two balloons measured over their entire control sequence.

experiments, as shown in Fig. 4(a). The allowable pressure range in the colon was defined as up to 7.6 kPa by considering results from routine colonoscopy in a clinical study [21]. The pressure P_{colon} applied to the inner wall of the colon during expansion of the balloon can be defined as the difference between the pressure P_{input_air} of the air inside the balloon and contraction pressure

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via restoring force $P_{silicone}$ of the silicone, as shown by the following equation:

$$P_{colon} = P_{input\_air} - P_{silicone} \tag{1}$$

Since the contraction pressure $P_{silicone}$ of the balloon upon expansion by P_{input_air} always has a positive value in the direction opposite to P_{input_air}, P_{colon} is always less than P_{input_air}. Considering that it is difficult to measure P_{colon} in an actual clinical environment, P_{input_air} was controlled within the allowable pressure range of 7.6 kPa in this study. A software timer was used to control the amount of input air to the balloon as a constant, and the air-pressure sensor was used to restrict the balloon pressure to within the allowable pressure range in the colon.

The shortening speed and air pressure of each balloon were selected as the evaluation criteria. The completion time for colon shortening was defined as the time from the instant the black reference point on the outer wall of the colon passed jig1 to when it arrived at jig2. The results of colon shortening are shown in Fig. 4(a). The completion time was measured using the video recorded with a USB camera, and the air pressure in each balloon was measured using air-pressure sensors in the pneumatic device. The speed of colon shortening was measured to be about 80 mm/min. Fig. 4(b) shows the air pressures inside the balloons measured during the colon shortening process. The maximum air pressures inside the two balloons were 6.63 kPa and 7.02 kPa.

III. Experimental Analysis for Defining the Straightening Strategy

A. Experimental Design

The large intestine of a human can be divided into the cecum, ascending colon, transverse colon, descending colon, sigmoid colon, rectum, and anal canal (Fig. 5(a)). The purpose of this analysis is to define the straightening strategy of the proposed system by analyzing the behavioral changes of the colon during sigmoid-colon handling. As shown in Fig. 5(b), four feature points A, B, C, and D are selected near the sigmoid colon, and their geometrical changes are analyzed.

It is assumed appropriate to define the straightening strategy for the sigmoid colon based on the clinical handling process of this study. Therefore, a colonoscopist who had experience with thousands of colonoscopy tests participated in this experiment. The expert performed experiments with handling the sigmoid colon using a commercial colonoscope (GIF-2T200, Olympus) and skilled insertion techniques. The colonoscopy training model (CM-15, KYOTO KAGAKU) was selected as the experimental testbed for this experiment (Fig. 5(b)). Since the CM-15 colon phantom has very similar characteristics to the human colon, it is widely used for colonoscopy insertion training and validation of robotic colonoscopy systems [22]–[24]. A 6-DOF optical tracking device (V120:Trio, OptiTrack) was used to measure the shape data of the sigmoid colon in real time (Fig. 6); since its ability to visualize the overall shape of the sigmoid colon with only visible markers is limited, the virtual marker P_4 was obtained from the position information

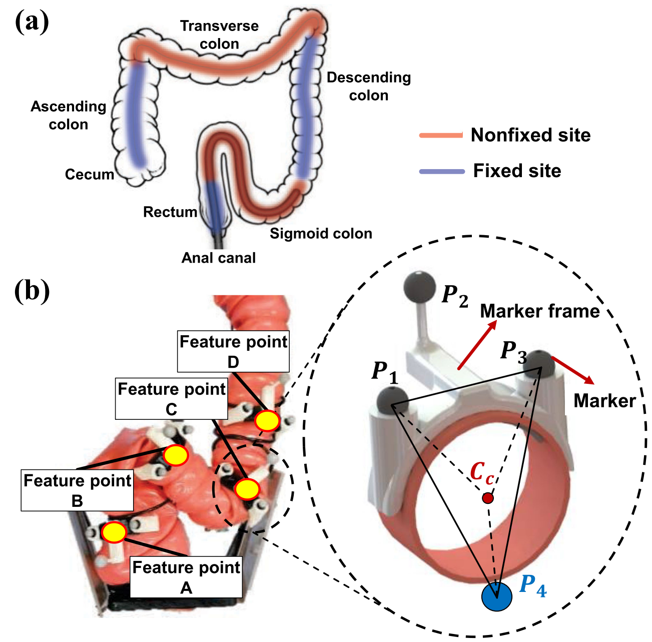

Fig. 5. (a) Anatomy of the human large intestine and (b) feature points selected to measure the shape data of the colon, along with the defined central point of the colon.

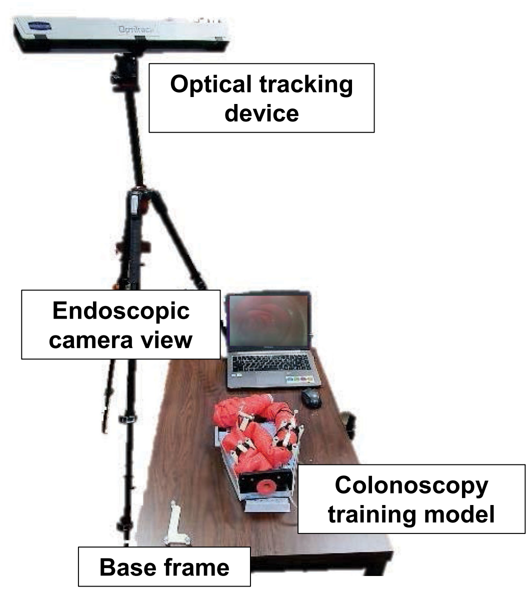

Fig. 6. Overview of the experimental environment with a 6-DOF optical tracking device.

of markers P_1, P_2, and P_3 measured using the optical tracking device, the geometrical information of the marker frame, and the outer diameter information of the colon phantom (Fig. 5(b)). The cross section of the colon was simplified and visualized as a planar triangle consisting of markers P_1, P_3, and P_4, and the center points of the planar triangles A_c, B_c, C_c, and D_c were assumed to be the center points of the colon phantom (Fig. 7).

The overall experimental environment is shown in Fig. 6. The expert performed the experiments five times. The camera

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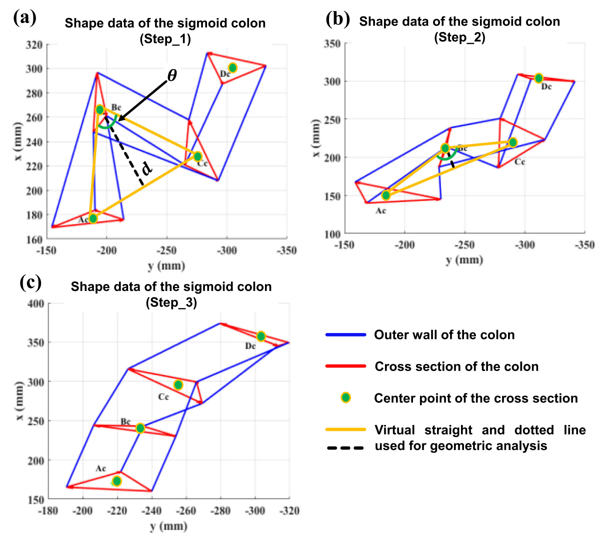

Fig. 7. Shape data of the sigmoid colon at each simplified step, measurement with an optical tracking device, and geometrical analysis: (a) access the beginning of the sigmoid colon, (b) perform skilled insertion techniques, and (c) continue insertion.

view was provided to the expert through a USB-type endoscopy camera attached to the end of the colonoscope, as shown in Fig. 6. After being introduced to the purpose and measurement methods of this experiment, the expert user was allowed 10 min of practice time.

The entire sigmoid-colon handling process was simplified to three steps in advance through literature related to the colonoscopies and the opinions of a colonoscopist:

Step_1) Access the beginning of the sigmoid colon through the anus.

Step_2) Perform skilled insertion techniques for sigmoid-colon straightening.

Step_3) Continue insertion after the sigmoid colon is straightened.

Fig. 7 shows the shape data measured from an optical tracking device for each simplified step, and the shape changes occurring between the steps were geometrically analyzed. Step_2) is an important step in the sigmoid-colon handling process. Therefore, the geometrical changes in the shape of the colon between Step_1) and Step_2) were analyzed carefully. Considering the overall shape changes to the colon in Step_2), the distance A_cB_c between points A and B, distance B_cC_c between points B and C, distance d between point B and line A_cC_c, sum of the changes in lines A_cB_c and B_cC_c, and angle θ between line A_cB_c and B_cC_c were selected as the analysis factors.

B. Results

Table I shows the results of the experiment. It was found that d always decreased in all the experimental cases, and θ always changed from an acute to obtuse angle, but changes in A_cB_c and B_cC_c were not always constant. However, $\Delta A_cB_c + \Delta B_cC_c$ had similar values within a certain range. It can thus

TABLE I
CHANGES IN REFERENCE LENGTHS AND ANGLES BETWEEN STEPS_1) AND 2) (REFER TO FIG. 7 FOR ALL NOTATIONS)

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
A_cB_c (mm)	77.01 ↓ 73.85	93.77 ↓ 77.07	90.24 ↓ 61.84	67.06 ↓ 67.78	90.44 ↓ 77.05
B_cC_c (mm)	55.40 ↓ 26.31	39.78 ↓ 19.72	17.80 ↓ 17.18	40.28 ↓ 8.76	32.71 ↓ 14.96
d (mm)	63.81 ↓ 37.57	76.14 ↓ 34.74	65.05 ↓ 29.17	60.60 ↓ 32.14	70.10 ↓ 26.21
$\Delta A_cB_c + \Delta B_cC_c$	32.17	36.76	29.05	30.68	31.05
θ (°)	68.85 ↓ 115.31	75.83 ↓ 119.56	77.97 ↓ 135.81	83.25 ↓ 118.60	68.85 ↓ 121.25

be said that the main purpose of the skilled insertion technique for sigmoid-colon handling is changing θ to an obtuse angle by moving point B closer to an arbitrary position near line A_cC_c. Therefore, the behavior of shortening the colon at the beginning of the sigmoid colon to change θ to an obtuse angle was defined as the straightening strategy.

IV. EXPERIMENTAL VALIDATION THROUGH USER TEST

A. Experimental Design

The purpose of this experiment was to verify whether the straightening of the sigmoid colon as well as successful insertion of the scope was possible through the proposed straightening strategy without skilled insertion techniques and its clinical effectiveness. The overview of the experimental environment with the testbed is shown in Fig. 8(a). This experiment is defined as the process of entering through the anus, straightening the sigmoid colon, and entering the descending colon. The geometric characteristics of the anal canal, rectum, sigmoid colon, and descending colon in the defined experimental procedure were considered for the experimental testbed design. The testbed was set up in the form of lengths of the various portions, i.e., anal canal = 30 mm, rectum = 120 mm, sigmoid colon = 400 mm, and descending colon = 300 mm, as shown in Fig. 8(b), considering the average geometric data of the colons investigated in the preclinical studies [25], [26].

Six subjects participated in this experiment. Two of them were experts who had experience with thousands of colonoscopy tests, and the other four were nonexperts who had little experience with colonoscopy tests. Experts performed insertion tasks using only a commercial colonoscope without the proposed system. The nonexperts were randomly divided into two groups. One group performed insertion tasks without the proposed system and the other group performed tasks with the proposed system.

Each task was repeated four times.

Fig. 9(a) shows the insertion process using only a colonoscope and can be simplified into three steps, as mentioned in Section 3. The insertion process using the proposed system and a colonoscope together can also be defined in three steps, as shown in Fig. 9(b).

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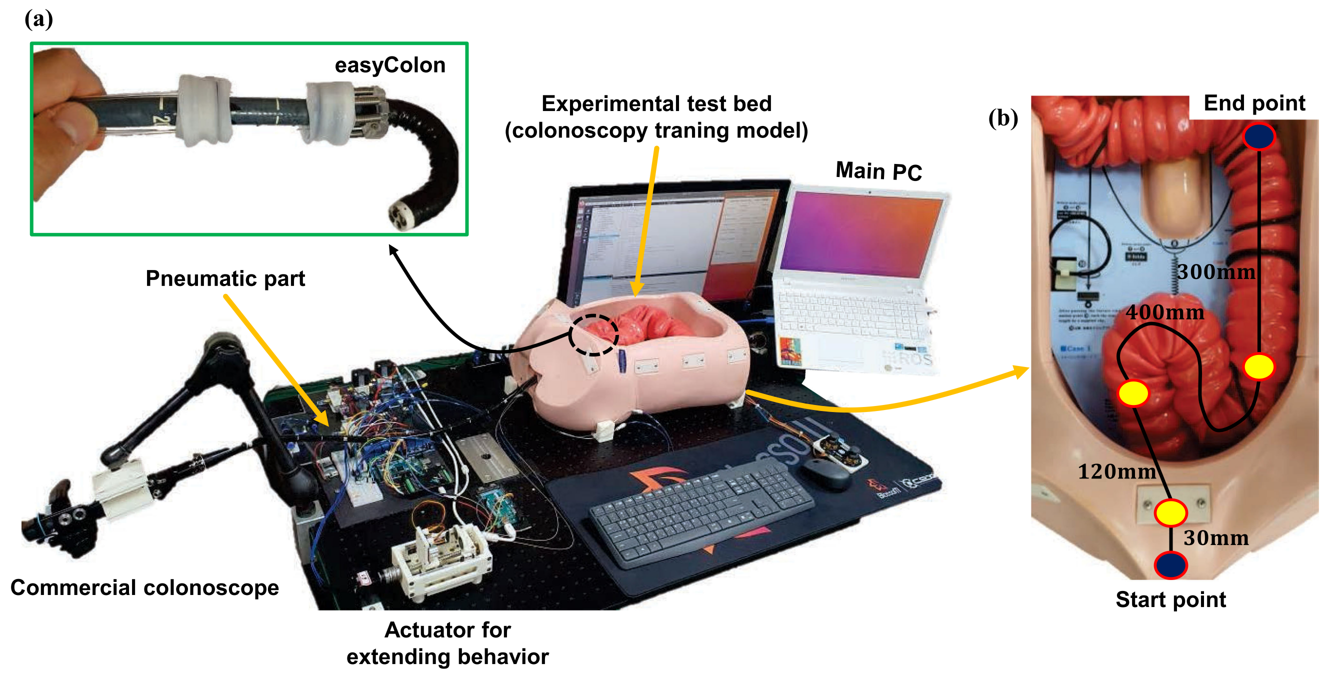

Fig. 8. (a) Overview of the experimental environment with the colonoscopy training model for the insertion process, including sigmoid colon straightening, and (b) geometric constraints of the sigmoid colon considering the average colon shape.

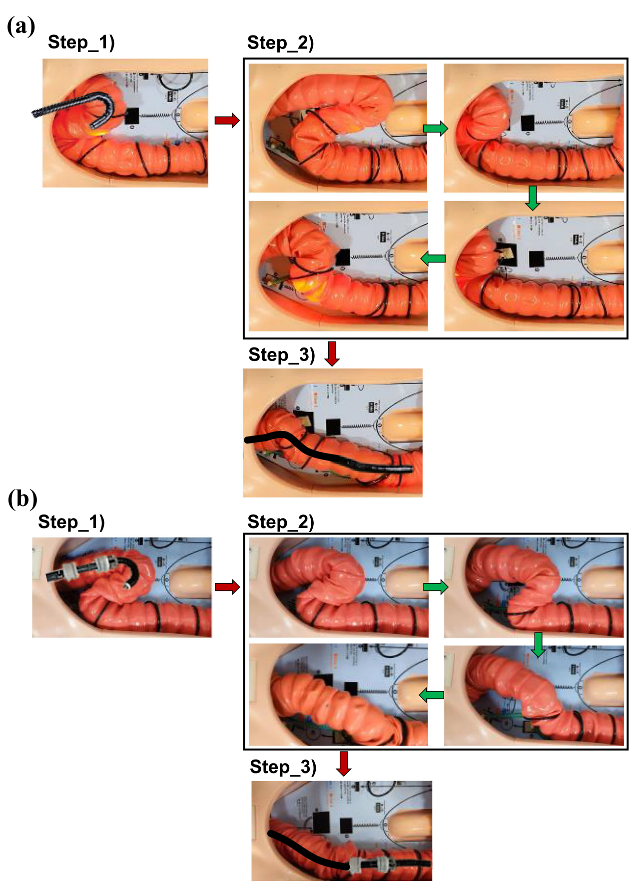

Fig. 9. (a) Clinical sigmoid-colon handling process using the commercial colonoscope and (b) process of sigmoid-colon straightening and colonoscope insertion using the proposed system mounted on a commercial colonoscope.

Step_1) Access the beginning of the sigmoid colon through the anus.

Step_2) Perform the peristaltic motion for sigmoid-colon straightening using the proposed system.

Step_3) Continue insertion after the sigmoid colon is straightened.

The completion time, success rate of insertion, and air pressure in each balloon were selected as the evaluation criteria. The completion time was defined as the time from the instant the colonoscope entered the start point to when it reached the endpoint (Fig. 8(b)). The completion time was measured using video footage recorded by the USB camera. Considering the opinions of a colonoscopist, the procedure was defined as a failure if the completion time exceeded 8 min. The air pressure of each balloon in Step_2) was measured using the air-pressure sensors in the pneumatic device.

B. Results

Table II shows the results of the user tests. It was confirmed that the air pressures inside balloon 1 and balloon 2 did not exceed 7.6 kPa in all instances during the sigmoid-colon straightening process when using the proposed system. For the two experts, the average completion times were measured as 105.75 s and 110.50 s, and the corresponding insertion success rates were 100%.

Nonexpert_1 and _2 belong to the group that did not use the proposed system, and nonexpert_3 and _4 belong to the group that used the proposed system. The average completion times of the nonexperts without using the proposed system were measured as 395 s and 375.50 s, and their insertion success rates

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TABLE II
EXPERIMENTAL RESULTS FOR THE INSERTION PROCESS IN THE USER TEST

		Trial 1	Trial 2	Trial 3	Trial 4	Average	Success rate
Completion time of expert_1 (s)		70	137	127	89	105.75	100%
Completion time of expert_2 (s)		152	92	103	95	110.50	100%
W/O easyColon	**Completion time of nonexpert_1 (s)**	365	Fail	438	382	395	75%
W/O easyColon	**Completion time of nonexpert_2 (s)**	Fail	309	442	Fail	375.50	50%
W/ easyColon	**Completion time of nonexpert_3 (s)**	301	290	295	323	302.25	100%
Maximum pressures of balloons 1 and 2 (kPa)		6.95 / 7.01	7.35 / 7.23	6.85 / 7.44	6.99 / 7.04		
W/ easyColon	**Completion time of nonexpert_4 (s)**	305	331	319	302	314.25	100%
Maximum pressures of balloons 1 and 2 (kPa)		7.18 / 7.42	7.12 / 7.23	7.05 / 6.95	7.07 / 6.87		

were 75% and 50%, respectively. The average completion times of the nonexperts using the proposed system were measured as 302.25 s and 314.25 s, and both insertions had success rates of 100%. It was thus confirmed that the completion time of the nonexpert group using the proposed system was shortened by about 20% and that the insertion success rate was improved by about 37.5%.

V. Comprehensive Discussion

A colonoscopy-assistance soft actuator for straightening the sigmoid colon, which can be mounted on a commercial colonoscope, is proposed. Since the proposed system is controlled within the allowable pressure range in the colon and can be mounted on a colonoscope because of its hollow-shaped design, it can be applied to clinical environments and extended to not only diagnosis but also surgical procedures.

In the system validation test, it was confirmed that the colon could be shortened through the proposed scheme, which simulates the peristaltic motion as the straightening strategy. In addition, the sigmoid colon was straightened using the proposed strategy, and it was confirmed that the colonoscope could be inserted without the skilled insertion techniques of an experienced colonoscopist in the user test.

In general, the operators teleoperate a robotic colonoscopy system using a master device. It is still a challenge for the operator to receive accurate physical information from the end-effector when using the master device to control the robot. Since the physical information from the end-effector must be accurate to ensure successful skilled insertion, additional methods will be required to insert the robotic colonoscopy system into the colon. Therefore, the proposed system is expected to be helpful not only for commercial colonoscopes but also for robotic colonoscopy systems.

In this study, six subjects participated in the user tests. Two of them were experts, and the other four were nonexperts. All nonexperts who participated in this experiment had experience with less than ten colonoscopy tests. Considering that the average completion time includes only successful trial cases and high insertion success rate, it was confirmed that the overall task performances of nonexperts who used the proposed system were better. In addition, since the six sequences of peristaltic motions defined as the straightening strategy were automatically repeated, the performance of the proposed system is expected to be consistent regardless of the user. Since the sample size is still small, it is expected that increasing the number of subjects and number of experimental repetitions would produce more reasonable results. However, considering the experts' completion times, the low speed of the proposed system should be improved for more effective use in clinical environments.

The expected problems in the pneumatic parts are the low speed at which the balloon expands and contracts to anchor the inner wall of the colon. The maximum pressure that can be used to prevent colon damage is 7.6 kPa, and the pressure increases in proportion to the speed of the input air. Therefore, the overall motion sequence time increased as the balloon's expanding time increased owing to the limited speed of the input air. The thickness of the balloon fabricated in this study was about 1 mm. In future research, the pressures required when the balloon is expanded could be minimized by reducing the thickness of the balloon. It is expected that the speed of the input air can be further increased by reducing the required pressure for balloon expansion. Small air tubes with an inner diameter of 1.5 mm and outer diameter of 2 mm were used to miniaturize the overall size of the proposed system. Since it required about 4 s to discharge the air inside the balloon completely through only the port of the solenoid valve, the overall motion sequence time increased. The air discharge time could be reduced by adding a vacuum ejector to the pneumatic part that controls the balloon. In this study, only the input air pressure was controlled under the simplified equation, without accurate mathematical modeling of the proposed system. The expansion behavior of the proposed system can be controlled more precisely using the system equation by considering the hyperelastic nature of the designed balloons; this could be a consideration in future research.

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The expected problem in the motor driving parts is also the low speed at which the actuator extends to shorten the colon. The overall motion sequence time increased as the leadscrew and linear guide were used to implement linear extending behaviors using the rotation servomotor. It is expected that the extending speed could be improved by replacing the rotation servomotor with a high-speed linear motor.

In this study, we focused on verifying whether the sigmoid colon could be straightened through the strategy of the proposed system and whether the colonoscope could be inserted without skilled techniques. Even after the sigmoid colon is straightened, it is important to successfully insert the device into sites with small radii of curvature, such as the colonic flexures. Hence, reducing the overall size of the proposed system through optimized arrangement of the wires, air tubes, and springs can help insertion in the colonic flexures. In addition, more reasonable results can be obtained if the effectiveness of using both the proposed system and a colonoscope together during the entire colonoscopy process can be verified.

VI. Conclusion and Further Work

This letter proposed a colonoscopy-assistance soft actuator for straightening the sigmoid colon, which can be mounted on a commercial colonoscope. The study results confirmed that the colon could be shortened through the proposed system, which simulates peristaltic motions, and the sigmoid colon could be straightened without the skilled insertion techniques of a colonoscopist.

In future work, we intend to reduce the overall size of the proposed system via optimal design and to perform verification experiments using both the proposed system and a colonoscope during the entire colonoscopy process to obtain more meaningful results. Furthermore, we intend to reduce the overall motion sequence time by improving the design limitations of the pneumatic and motor driving parts.

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