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A Soft Robotic Haptic Feedback Glove for Colonoscopy Procedures

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***Abstract*— This paper presents a proof-of-concept soft robotic glove that provides haptic feedback to the surgeon's hand during interventional endoscopy procedures, specifically colonoscopy. The glove is connected to a force sensing soft robotic sleeve that is mounted onto a colonoscope. The glove consists of pneumatic actuators that inflate in proportion to the incident forces on the soft robotic sleeve. Thus, the glove is capable of alerting the surgeon of potentially dangerous forces exerted on the colon wall by the colonoscope during the navigation. The proposed glove is adaptable to a variety of hand sizes. It features modular actuators that facilitate convenient and rapid assembly and attachment before the procedure and removal afterward. The glove is calibrated to respond to incident forces on the soft robotic sleeve ranging from 0-3 N. The glove's actuators are able to reach an internal pressure of 53 kPa and exert forces up to 20 N, thereby relaying and amplifying the force exerted by the colonoscope on the colon to the surgeon's hand.**

I. INTRODUCTION

Robot-assisted minimally invasive surgery (R-MIS) has countless benefits over open surgery, from shorter recovery times and lower risk procedures for the patient to higher accuracy and broader capabilities for the surgeon [1]. However, a significant detriment to these procedures is that current R-MIS systems lack haptic feedback. This forces the surgeon to depend merely on visual cues, such as the deformation of tissue under load, to estimate the forces [1], [2]. The likely outcome of misreading these cues is torn tissue, patient discomfort, or broken sutures [3]. In manual MIS surgeries, surgeons interact with patients via rigid instruments with a long shaft, this reduces tactile and force feedback and leads to increased intra-operative injuries. In R-MIS surgeries, the tele-operated nature of robotic instruments removes the direct tactile connection between the patient and the surgeon [4].

Lack of haptic feedback is particularly detrimental when the surgical instrument is flexible i.e, flexible endoscopes, as the presence of friction causes a reduction in rigid transmission of forces from the contacted tissue to the surgeon [5]–[7]. Thus, haptic feedback is vital for both conventional and robot-assisted endoscopies. A recent study evaluating an Endoscopic Operation Robot (EOR) concluded that the absence of haptic feedback resulted in higher incidences of overstretching of the sigmoid colon in a colonoscopy training model [8]. Consequently, the lack of haptic feedback during colonoscopy results in application of excessive forces by the surgeon. This can cause tissue damage [9] and other severe adverse events (SAEs) such as abdominal pain, bleeding, perforation and splenic injury [10]. One study noted that the peak pushing force during a colonoscopy exceeded 40 N, and forces were greater than 10 N for 5% of procedure time [11]. Another study observed that the peak force exerted on the colon wall was approximately 12 N, with an average force value of 0.284 N [12]. Sensing systems have been developed to address the issues posed by excessive force in colonoscopies, including distal tip force sensing [13], shape sensing of the colonoscope using fiber Bragg gratings (FBG) [14], and magnetic force tracking [15]. Feedback interfaces have also been utilized to mitigate application of excessive forces during colonoscopy, such as a master-slave telesurgical robot with haptic feedback [16], a sensorized

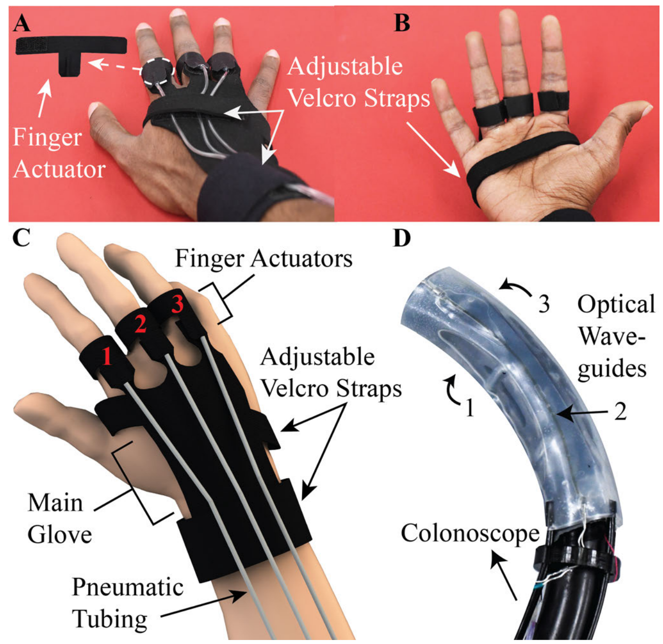

Fig. 1. A)-B) Soft robotic haptic feedback glove prototype front view A) and rear view B) showing adjustable straps wrapped across palm. C) CAD model showing glove's components, including finger actuators (numbered), main glove structure with adjustable Velcro straps, and tubing. D) Soft robotic sleeve showing three optical waveguides.

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gripper providing audio-visual cues [17], and a virtual reality (VR) based haptic feedback simulator [18].

Haptic feedback is normally provided via cutaneous interactions to sensitive areas such as the palm and fingertips [19]. Thus, most devices that provide haptic or tactile feedback are in the form of gloves designed to be worn around the user's hand [20]. However, most haptic feedback gloves cater to applications such as virtual or augmented reality (VR/AR), augmentative and alternative communication (AAC), and medical rehabilitation [21]. There appears to be a dearth of haptic feedback gloves used specifically for MIS, as most existing MIS haptic systems are in the form of standalone actuators or tactile arrays [22], [23]. Furthermore, most haptic feedback gloves largely utilize rigid commercial sensors and actuators which hinder their flexibility [21]. This can be detrimental for surgical procedures which require precise and dexterous movements of the surgeon's hand, ultimately limiting the use of these devices in real clinical practice. A soft robotic haptic feedback glove would alleviate this issue as it would provide improved mechanical compliance and flexibility compared to their rigid counterparts. However, current applications of soft robotic gloves have predominantly focused on robotic rehabilitation for stroke and spinal cord injuries [24]–[27].

This work presents a soft robotic glove that aims at restoring and amplifying haptic feedback directly to the surgeon's hand to facilitate navigation during colonoscopic procedures (Fig. 1, A-C). In our previous work, we introduced a soft robotic sleeve [28] that can detect forces between a colonoscope and colon walls during navigation (Fig. 1, D). The glove receives force input from the soft robotic sleeve wrapped around the colonoscope. Any incident force on the sleeve, during endoscopic navigation, is relayed to the surgeon's hand as haptic feedback through proportional inflation of the glove's pneumatic actuators.

II. MATERIALS AND METHODS

This section describes the soft robotic haptic feedback glove design, fabrication, and fluidic control circuit and associated pulse-width modulation (PWM) control approach.

A. Glove Design

The glove design consists of three pneumatic actuators, each wrapped around the index, middle and ring fingers respectively, and connected the main glove piece (Fig. 1 C). Pneumatic actuation was selected as a viable method to deliver scalable haptic feedback directly to the surgeon's hand. Compared to other methods such as electric motor and cable driven actuation, pneumatic actuation is more advantageous due to its high power-to-weight ratio, simplicity of fabrication, low cost, and increased safety due to fewer moving components [22], [29]–[31]. Furthermore, pneumatic actuators provide a more natural sensation of haptic feedback compared to vibro-tactile actuators. For example, when a colonoscope presses against the colon wall, the surgeon feels a resistive force whose sensation can be mimicked by pneumatic pressure. In contrast, the inherent vibration or electro-stimulation of a vibrotactile actuator does not accurately represent the nature and sensation of the incident force produced in this scenario [32], [33].

The actuators on the fingers are attached to the main glove piece in a modular fashion using adjustable Velcro® straps. This allows the glove to be quickly adapted to various users' hand sizes (i.e. interventional endoscopists). The finger actuators are designed to be wrapped around the proximal phalanges of the hand and inflate on the dorsal side (Fig. 1 A, C). Similarly, the main glove piece is attached to the dorsal side of the hand with a singular strap securing it across the palmar side around the wrist (Fig. 1 B). The components of the glove do not cover the fingertips or interfere with grasping of the palm. This allows the surgeon to operate the endoscope shaft and knobs without the glove hindering palm and fingertip dexterity. Loss of such dexterity could hamper handling and manipulation of the endoscope during the procedure. In contrast, most commercial haptic feedback gloves use vibrotactile or linear resonant actuators (LRAs) mounted onto the palm and fingertips [20]. This reduces palm and fingertip dexterity, rendering such gloves unsuitable for haptic feedback in endoscopies.

The number of finger actuators in the proposed glove can be varied depending on the number of sensors attached to the endoscope. For the purpose of this study, such sensors are embedded in a soft robotic sleeve wrapped around a colonoscope [28]. The soft robotic sleeve has three optical waveguides to serve as force sensors, and each of them is connected to a finger actuator (Fig. 1, C-D). Incident forces on each optical waveguide cause individual inflation of the corresponding actuator. The actuators are arranged on the glove to match the spatial orientation of the sleeve, i.e, the first actuator on the index finger maps force input from the first, leftmost waveguide (Fig. 1, C-D). Whereas the second actuator on the middle finger maps force input from the second, middle waveguide on the sleeve (Fig. 1, C-D). Similarly, the third actuator inflates when there is incident force on the third, rightmost waveguide (Fig. 1, C-D). Thus, the surgeon is able to ascertain not only the magnitude of the incident force on the colonoscope but also its direction based on the specific waveguide that detects the force.

Overall, the glove is lightweight (30 g), with a low vertical profile of 1 mm and minimal wiring; three tubes measuring 2.38 mm in outer diameter (OD) are attached to the three soft pneumatic actuators. This ensures ergonomic comfort for the wearer. The actuators also have a low vertical profile (1.5 mm) when fully inflated. This reduces the risk of force exchange between two touching actuators which could bias the haptic feedback. In addition, the glove is designed to be disposable after each surgical procedure, thereby preventing any cross contamination. Flexible endoscopes and associated devices can become heavily contaminated with blood and secretions during use. This can potentially cause severe infections in the patient [34], [35]. Hence, it is vital that the device is easily replaced between surgical procedures.

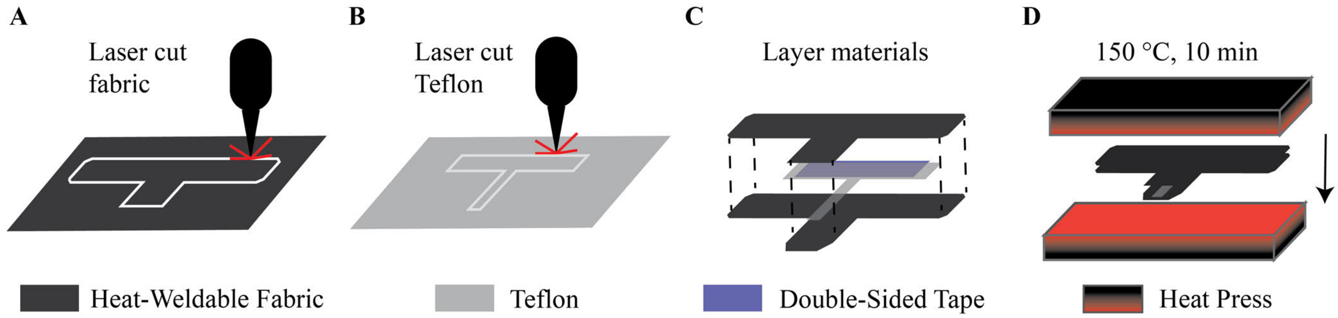

Fig. 2. Soft robotic haptic feedback glove fabrication. A)-B) Heat weldable fabric and Teflon are laser cut into the desired pattern. C) Materials are layered and laminated using double sided tape. D) Materials are sealed using heat press to form the completed soft actuator.

B. Fabrication

The finger actuators are made from a combination of materials. First, heat weldable fabric (Seattle Fabrics, Inc.) and Teflon (McMaster-Carr Supply Company) are laser-cut (VLS6.6, Universal Laser Systems, Inc.) into a T-shaped pattern (Fig. 2, A-B). Then, the Teflon is sandwiched between two pieces of the heat weldable fabric using double sided tape (Fig. 2, C). The double sided tape ensures that the Teflon is held in place between the two layers of fabric to form a symmetric air pocket in the actuator. Finally, the layered materials are sealed together using a heat press at 150° C for 10 min (Fig. 2, D). This lamination process forms a completed, sealed actuator. Tubing is inserted into the actuators and secured using a hot glue gun (Surebonder). Adhesive Velcro® straps are then attached to the actuators. The main glove serves as a connection between the finger actuators and the wrist, providing a secure fit. The main glove is cut out from 1 mm thick Neoprene (SewSwank) into the desired shape. Velcro® straps are then attached to the glove in order to adjust to the user's hand size. The entire fabrication process is sew free, allowing easy and rapid manufacturing. The actuators are disposable to avoid contamination and the need for sterilization. Total fabrication time for the soft robotic glove is 1 hour.

C. Control

The actuators on the glove (Fig. 3, A, 1) are connected to a fluidic control board, with three solenoid valves (Fig. 3, A-B, 2) attached to a manifold (GVP-321C-24D, Nitra® Pneumatics). The valves are controlled via a 4-channel MOSFET switch module (IRF540, NOYITO) (Fig. 3, A-B, 3) connected to an Arduino® Mega 2560 micro-controller (Fig. 3, A-B, 4). Each valve is connected to an actuator via flexible plastic tubing (2.38 mm OD, McMaster-Carr Supply Company). The control algorithm uses pulse width modulation (PWM) to vary the duty cycle controlling the solenoid valves, based on the input from the soft robotic sleeve's sensors (Fig. 3, A, 5). Thus, the magnitude of incident force on the soft sensors determines the value of the duty cycle, triggering a proportional inflation of the actuators. The duty cycle equation is as follows:

$$Duty\ Cycle\ [\%] = Loss\ (dB)\ \times\ C \tag{1}$$

The 8-bit duty cycle is determined by the $Loss(dB)$ multiplied by a scalar variable C. The equation is calibrated such that the variable C scales the optical loss from the sensors to ensure that the duty cycle is at 100% when the incident force is at a maximum. In this study, the maximum force was chosen to be 3 N. However, this range can be tuned and increased depending on the surgon's preference and the patient's conditions. Thus, C scales the optical loss such that the loss value at 3 N results in a 100% duty cycle. The optical loss from the soft sleeve ranged between 3.5–4 dB depending on the particular waveguide. This slight variation is due to minor manufacturing inconsistencies of the soft optical sensors. Specifically, the loss appears to saturate at the aforementioned value as the incident force on the sensor increases from 2 N to 3 N. Hence, a C value of 30 was chosen such that the duty cycle reaches 100% as the incident force increases beyond 2 N towards the maximum force value of 3 N. The optical loss from the waveguides on the soft robotic sleeve is calculated as follows:

$$Loss\ (dB) = 10\ \times\ log_{10}(I_o/I) \tag{2}$$

where I_o is the output power of the undeformed waveguide on the soft robotic sleeve when there is no incident force, and I is the power through the waveguide when the sensor is deformed due to the incident force. The change in output power I is measured as a change in voltage recorded by the photodiodes in the soft robotic sleeve circuit. The optoelectronic setup is a voltage converter circuit which consists of infrared LEDs (TSHA4400, VishaySemiconductors) that transmit light through the waveguides to a receiving photodiode (SFH 229, OSRAMOpto Semiconductors). The photo-diodes are connected to an op-amp (LM358N, Texas Instruments), 470 kΩ resistor, and a 4700 pF capacitor. The circuit is powered by a ±12 V and 5 V power supply.

III. RESULTS AND DISCUSSION

This section describes the experiments performed in this work including actuator pressure holding validation, force calibration of the soft sleeve with the haptic glove, blocked force amplification of the actuators, *in-vitro* testing in a mock colon, and prototype evaluation from an expert interventional endoscopist.

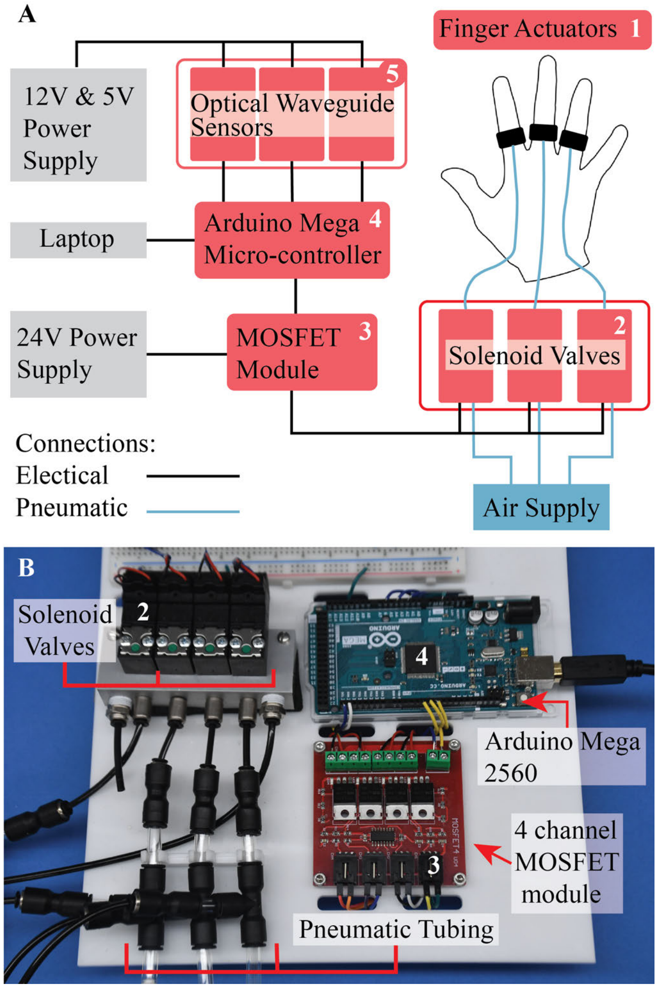

Fig. 3. A) Block diagram showing control circuit. B) Fluidic control board.

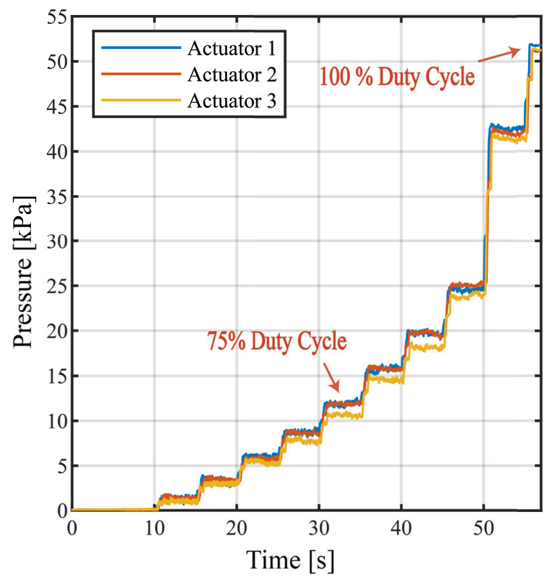

Fig. 4. Test results displaying incremental increase in actuator pressure due to corresponding increase in PWM duty cycle.

A. Pressure Holding Validation

The actuators on the soft robotic haptic glove were subjected to incremental changes in the PWM duty cycle and the resultant internal pressure due to inflation was measured using a pressure transducer (BSP000W, Balluf Inc.). This test was performed in order to highlight the ability of the glove's actuators to achieve and hold discrete internal pressure values. This test also helps ascertain the relationship between duty cycle % and the pressure behaviour of the actuators. This is crucial as the surgeon must be able to easily distinguish changes in actuator pressure as the force on the sensor changes. The control code was set to vary the duty cycle by 5% increments every 5 s. The test was performed for a time range of 60 s. Based on Eq. 1, the PWM frequency was set to 45 Hz. At duty cycle values below 45%, the input signals from the micro-controller to the solenoid valves are too fast to register [31] and the actuator does not inflate. Therefore, for the purpose of this test, the inflation of actuators was constrained to begin at a 50% duty cycle. This is beneficial as the duty cycle can be set to trigger inflation of the actuators only if the input (i.e., force on the soft robotic sleeve) exceeds a certain threshold. This can help prevent the glove from being overly sensitive to input forces of minor magnitude (see Section III-B). As the duty cycle increases with time, the actuators were able to inflate to different, discrete pressures (Fig. 4). Also, the actuators were able to hold the pressure at different duty cycle values in a constant manner with minimal fluctuations. It is worthy to note the exponential relationship between the pressure in the actuator and duty cycle %. For example, at t = 45 s the duty cycle increases from 85% to 90%, and the corresponding pressure increases from 20 kPa to 25 kPa. At t = 50 s, the duty cycle increases by the same amount from 90% to 95%; however, the pressure increases sharply from 25 kPa to 43 kPa. At 100% duty cycle the pressure reaches a maximum value of 53 kPa. Thus, as the duty cycle increases towards the higher end of its operating range, the subsequent pressure increases are greater. The non linearity in pressure response allows the actuators to amplify haptic feedback as the forces on the colonoscope reach potentially dangerous levels. This non-linear rise in pressure can be programmed so that this transition can occur over any arbitrary range of forces on the sleeve.

B. Force Calibration

The soft robotic sleeve was subject to a force compression calibration test (Fig. 5) using an Instron universal testing system (5943, Instron®). The internal pressure of the actuators is measured using a pressure transducer (BSP000W, Balluf Inc.) in-line with the pneumatic circuit. Each waveguide on the sleeve was tested separately using the Instron and the corresponding actuator pressure was recorded. A 4×4 mm indenter (Fig. 5, inset) is 3D printed (Form2, Formlabs) and securely fastened to the end of a 50 N load cell. The Instron is programmed to move vertically downward at a rate of 5 mm/min such that force applied on the sleeve increases from 0 to 3 N. As the indenter presses down on the soft robotic sleeve, light transmission across the waveguide

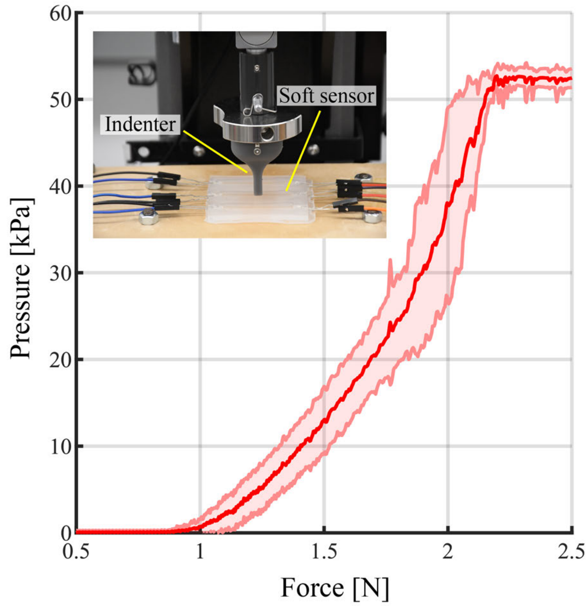

Fig. 5. Test results displaying actuator inflation pressure in response to incident force on soft robotic sleeve.

decreases and this causes a change in signal voltage. The system registers this as an optical loss (Eq. 2) and the inflation of the actuators is triggered in the glove (Eq. 1). The control algorithm is adjusted so that only forces greater than 1 N trigger actuator inflation. This is to ensure that the surgeon is notified of larger, potentially dangerous forces onto the colon while ignoring smaller, inconsequential forces. An overly sensitive sensor could cause actuator inflation due to minuscule force interactions and unnecessarily distract the surgeon. However, this force threshold can be changed as necessary depending on the nature of the surgical procedure, patient's conditions, and surgeon's preference. As the force increases beyond 1 N, the actuators inflate and the internal pressure rises correspondingly (Fig. 5). Once the force reaches 2.2 N, the duty cycle reaches its maximum value of 100% which causes the internal pressure in the actuators to saturate at 53 kPa. In a real surgical scenario, this would mean that the force on the sensor reaches a dangerous level hence the actuators inflate completely to alert the surgeon. Any further increase in force (from 2.2 N up to 3 N) results in the actuators continuing to stay inflated at maximum pressure until mitigating measures are taken by the surgeon to reduce force on the sensor (i.e., readjusting the colonoscope position and orientation during navigation). Thus, this experiment demonstrates the ability of the actuators to apply haptic feedback in a manner proportional to the incident force on the sensor.

C. *Force Amplification*

This test was performed to evaluate the force exerted by the actuators when they inflate due to the force applied on the soft robotic sleeve (Fig. 6, A). This was done in order to ascertain the ratio of force amplification or mapping i.e., the ratio of incident force to output force produced as haptic feedback. A 1 kN load cell force transducer (Fig. 6, B) was attached to a 3D printed test rig (CR-6 SE, Creality). The rig was then fastened to an optical breadboard (Thorlabs Inc.) to ensure that the transducer is constrained in all directions. A finger actuator was fastened directly underneath the force transducer rig and subject to blocked force testing. The soft robotic sleeve was subjected to incident force using an Instron (as described in Section III-B). As the sleeve was pressed by the indenter, the control system triggers inflation in the finger actuator. The force due to inflation was subsequently recorded by the 1 kN force transducer. As seen in Fig. 6, B the force applied by the indenter ranged between 0-3 N. As the incident force increases, the exerted output force by the actuators also increases. The actuator begins to exert a force as the input force nears 0.75 N. The output force increases until about 2.2 N where it saturates at a maximum mean value of 20 N. The force exerted by the actuator was approximately nine times larger in proportion to the force input. This test demonstrates the ability of the glove to provide haptic feedback through amplification of input forces to a magnitude that could be easily noticed and felt by the surgeon during a colonoscopy procedure.

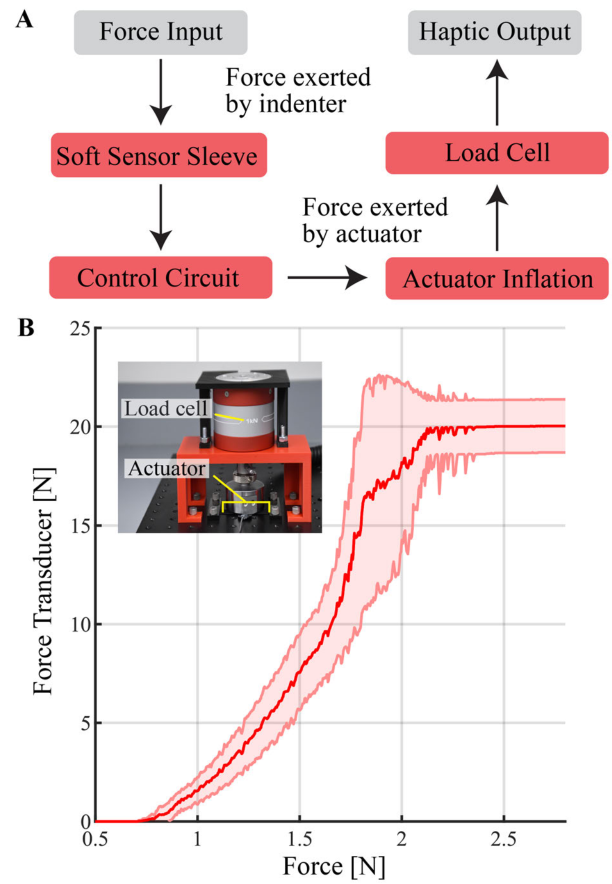

Fig. 6. Force amplification test. A) Block diagram showing test setup. B) Test results of the blocked force exerted by the inflating actuator in response to incident force on the soft robotic sleeve.

D. *In-Vitro Validation*

An *in-vitro* test was performed by simulating a colonoscopy procedure. The soft robotic sleeve was wrapped around a colonoscope model. An artificial colon model was created from thermoplastic elastomer (TPE) (Stretchlon® 200, FibreGlast, USA) and the colonoscope was inserted into it (Fig. 7, A). During navigation, when the colonoscope pushes on the colon wall, the light transmission in the optical waveguides of the soft robotic sleeve decreases and the voltage values drop. This increases the value of the duty cycle and triggers the inflation of the actuators on the soft robotic haptic glove. As described in Section II-A, the three optical waveguides in the soft robotic sleeve are connected independently to the three finger actuators on the soft robotic glove. This allows the actuators to map the magnitude and direction of incident force on each waveguide. As seen in Fig. 7, B, the three sub-figures represent each actuator and its corresponding waveguide. When the optical waveguides on the colonoscope push against the colon wall, the voltage difference increases. This causes the PWM duty cycle to increase, resulting in inflation of the actuators. The duty cycle in the actuator increases instantaneously as the voltage difference increases in the optical waveguides. Initially, between time interval of 1 s to 5 s, sensor 1 records a rise in voltage, thereby triggering actuator 1. Sensor 2 and actuator 2 are triggered shortly thereafter from 5 s to 10 s. Sensor 3 records a rise in voltage at time t = 15 s, which causes the duty cycle to rise. Lastly, at the time interval between 20 s and 40 s, all three sensors experience an incident force, such that all three actuators inflate as seen by the sharp peaks in duty cycle values (Fig. 7, B). This demonstrates the preliminary effectiveness of the soft glove in providing haptic feedback in endoscopic procedures where one or more sensors detect incident force.

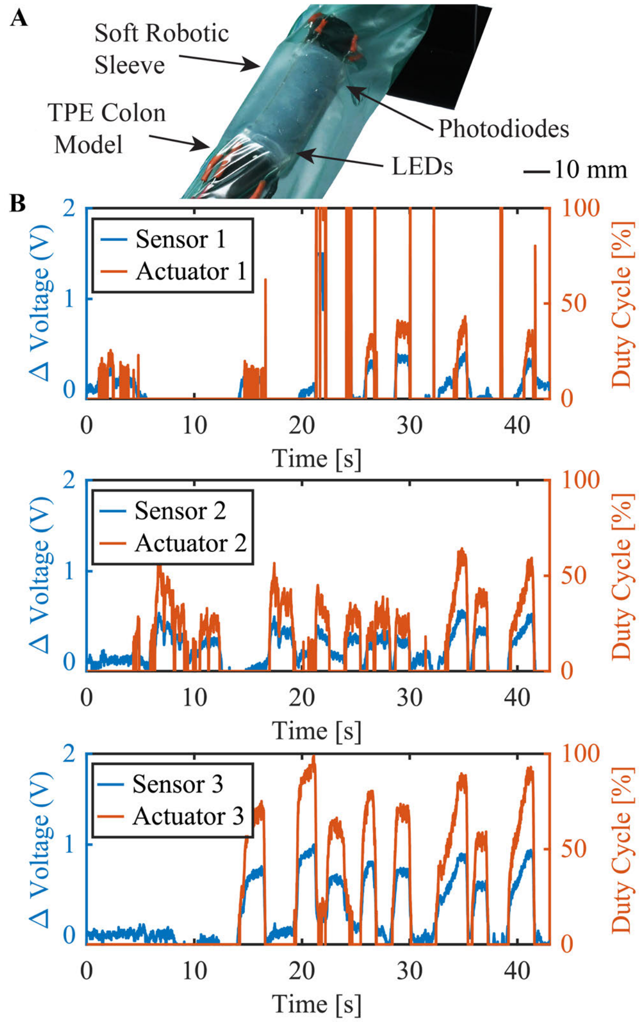

Fig. 7. *In-vitro* validation test. A) Setup. B) Results.

E. Clinical User Evaluation

The soft robotic glove was evaluated by an expert surgeon by performing a simulated colonoscopy *in-vitro* (Fig. 8). On Feb 18, 2021, the Charles River Campus IRB at Boston University determined that this study is exempt in accordance with CFR 46.104(d)(3) as the information obtained is recorded such that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects, and benign behavioral interventions are brief in duration, harmless, painless, and not physically invasive.

First, parameters including comfort, wearability, and usability were qualitatively evaluated. The results showed that the glove's design does not obstruct fingers and overall hand motions during the procedure (Fig. 9), thus enabling endoscope manipulation in a transparent manner. The subject noted that the glove was ergonomic, comfortable while performing the procedure, and could be worn with minimal to no assistance. Four *in-vitro* tests were then performed by the surgeon with different sensitivity levels of haptic feedback in the glove. In the first test, colon navigation was performed without using the haptic glove, thus no haptic feedback was present. In the second test, the haptic glove was connected to the colonoscope and pneumatic inflation was obtained in the fingers during navigation. In the third and fourth test, haptic feedback was still enabled, however the sensitivity of the soft sensor sleeve was decreased to 85% and 70% respectively. This was achieved by changing the scalar variable C (Section II-C) to 25 and 20 respectively. A NASA Taskload Index (TLX) [36] was used to evaluate each test and measure the performance of the haptic glove during a colonoscopy. The NASA TLX is a multidimensional rating procedure that provides a cumulative workload score for a specific task based on six sub-scales: Mental Demand, Physical Demand, Temporal Demand, Efforts, Performance, and Frustration. Higher ratings for mental demand, physical demand, temporal demand, efforts, and frustration indicate high discomfort in the task. A high rating in the performance sub-scale indicates a good subject experience in the task. The subject performs a pair-wise comparison of all six sub-scales and a weight is assigned to each sub-scale based on the comparison. After each task, the subject assigns a rating to each sub-scale on a rating scale which ranges from 0 to 100 with increments of 5. The weights are then multiplied with the ratings to obtain the adjusted ratings. The sum of the adjusted ratings is divided by the total weight to obtain the workload score of the task. Table I shows the workload scores for all four tests performed by the expert interventional endoscopist. A lower workload score

Fig. 8. *In-vitro* test preformed by an expert interventional endoscopist. A) The colonoscope enters the mock colon. B) Surgeon maneuvers colonoscope around a colon curvature. C) Colonoscope contacts colon wall (applying excessive force) and soft glove inflates providing haptic feedback to the surgeon's hand. Surgeon takes corrective action to redirect colonoscope. D) Colonoscope navigates through the critical curvature. E) Colonoscope reaches colon target region.

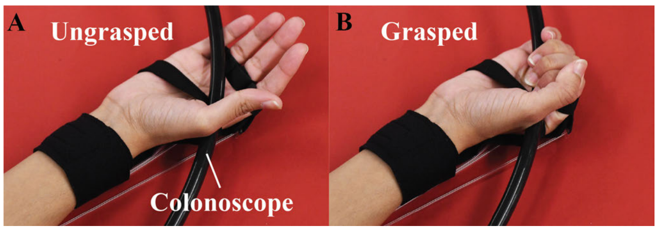

Fig. 9. A) Ungrasped hand with mounted glove and colonoscope. B) Hand grasping colonoscope with no impediment from the glove.

relates to better efficiency and less discomfort. As seen in Table I, the workload score for the first test in which haptic feedback was absent was 69.7, the highest of all four tests. Moreover, mental demand, physical demand, effort, and frustration were rated as very high for the first test, which demonstrates the increase in discomfort for surgeons when no haptic feedback is present in colonoscopy procedures. In the second test, with haptic feedback enabled and 100% sensor sensitivity, a workload score of 49 was achieved (Table I). There was a significant decrease in the ratings for mental demand, physical demand, and frustration. Moreover, the performance parameter received a better rating for the second test compared to the first. This demonstrates the effectiveness of the haptic glove in reducing workload and burden on surgeons. For the third test, the sensor sensitivity was reduced to 85% and the total workload score improved to 45.3 (Table I). Mental demand and physical demand were rated similar to the second test but the rating for frustration and effort decreased significantly, indicating a better experience by the subject. The subject also expressed that 85% sensor sensitivity avoided unnecessary and minor pneumatic inflation (mainly reported during the insertion process), making the haptic glove more effective. For the fourth and final test, the sensor sensitivity was reduced to 70% and the resultant workload score increased to 57.7 (Table I). The ratings for mental demand, physical demand, effort, and frustration were still lower than the first test with no haptic feedback, but were higher than the second and third test. This suggests that keeping the scalar variable C in the control logic at a value of 25 optimizes the effectiveness of the haptic glove system. The surgeon was aided by visual feedback in addition to haptic feedback due to the transparency of the TPE colon. However, visual feedback was present in both haptic feedback and no haptic feedback tests, serving as a control.

TABLE I

NASA TLX WORKLOAD SCORES FOR THE IN-VITRO TEST

Test	Colon Navigation	Sensitivity	TLX Workload
1	No Haptic Feedback	N/A	69.7
2	Haptic Feedback	100% (C = 30)	49
3	Haptic Feedback	85% (C = 25)	45.3
4	Haptic Feedback	70% (C = 20)	57.7

CONCLUSION

This study describes an initial, proof-of-concept soft robotic haptic feedback glove for colonoscopies. The glove is linked to a soft robotic sleeve that allows force detection between the colon and the colonoscope during endoscopic navigation. The glove is able to respond to incident forces on the colonoscope by inflating pneumatic actuators on the fingers, thereby providing haptic feedback to the surgeon. The glove is made via a simple, sew-less fabrication process that allows inexpensive and rapid fabrication. The glove is controlled via a PWM control approach that determines the duty cycle of the solenoid valves based on the optical loss from the soft robotic sleeve. The sensor is able to respond to forces greater than 1 N and achieves full inflation from 2.2 to 3 N, thereby alerting the surgeon to potential dangerous forces in the colon. This range of forces can be fine tuned in the future to account for the large variation in peak forces experienced during colonoscopic procedures. The glove is able to effectively amplify incident forces by a factor of nine. This allows the glove to alert the surgeon using easily noticeable haptic cues. The glove was further evaluated in an *in-vitro* setting, wherein an expert surgical endoscopist rated the cumulative workload of a simulated colonoscopy procedure with and without haptic feedback. It was shown that haptic feedback from the glove significantly reduced the workload of colonoscopic navigation from a TLX value of 69.7 (without haptic feedback) to 45.3 (with haptic feedback). We concluded that the glove is effective in pressurizing the fingers of the wearer proportionally to the amount of force exerted on a colon wall during a colonoscopy procedure, providing haptic feedback. The glove also provides a spatial mapping of the incident force in different directions.

The next steps for this study would be to determine the adaptability of the haptic glove to a larger pool of users with various skill levels (i.e., expert and novice interventional endoscopists). Further, the glove could be adapted to provide haptic feedback for other robotic-assisted surgical procedures, e.g., laparoscopy and other interventional endoscopy procedures, and interfaced with any type of on-board sensing technologies. Lastly, the design aspects of the glove will be improved, e.g., the glove will have an ambidextral configuration that fits both left and right handed users.

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