Design and evaluation of a foot-controlled robotic system for endoscopic surgery

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***Abstract*—In traditional endoscopic surgery, the surgeon manipulating the endoscopic instruments is supported by an assistant controlling the endoscope, where their coordination may be affected by communication errors. To address this issue, we introduce a foot interface controlled robotic endoscopic system, enabling the surgeon to simultaneously operate the endoscope and instruments. The system consists of a foot interface using four degrees of freedom (DoFs) foot gestures and a robotic driving system for a commercial flexible endoscope. The proposed robotic system was validated in teleoperation experiments performed by ten subjects, where foot teleoperation was compared with hand teleoperation and direct control of the endoscope with two hands. The participants could successfully teleoperate the endoscope with foot teleoperation and exhibited 40% faster task completion as with direct control. They found both foot and hand teleoperations comfortable and intuitive. Although hand teleoperation enabled the best performance, only foot teleoperation allows simultaneous control of three instruments.**

***Index Terms*—Foot control, teleoperation, endoscope manipulation, robot-assisted surgery.**

I. INTRODUCTION

Minimally invasive surgery (MIS) gives access to the surgical site through a natural orifice or small incisions. This causes less damage to the patients' body and enabling faster recovery [1] than open surgery. The MIS procedure requires at least three instruments including the camera. In current practice, one of these instruments is controlled by an assistant, requiring excellent coordination with the surgeon. However, this coordination can be affected by communication errors and results in delay and safety issues [2], [3].

A robotic system enabling a surgeon to control three tools represents a possible solution to this issue. For instance, some systems provide autonomous positioning of the endoscope [4]–[6] using visual servoing from the camera images. Regardless practical issues such as blood occluding the image, the automatic endoscope positioning may not match the surgeon's intention and may cause safety issues [7]. Therefore, most the current robotic surgery systems use hand or hand-free interfaces to control the third tool.

A third tool can be controlled sequentially with the hands *i*) through a clutch-based interface or *ii*) using a separate interface. In *clutch-based hand control*, the operator uses the same hand interface to control different surgical tools, with clutch buttons or pedals to activate the swapping to the third tool. For example, in the flexible endoscopic system K-Flex [8], the operator can press a pedal to swap between a surgical forceps and flexible overtube. Similarly, the Da Vinci Si system [9] provides a built-in master console with hand controllers and footswitches for swapping the arm control. In *separate interface hand control*, the third tool is either teleoperated by the hands using a separate control interface, or directly controlled by hands. For example, in the Medrobotics Flex system [10], the operator first navigates the endoscope to the target area using a joystick and then switches to the two manual instruments. However, with all these modalities using sequential hand control, it is not possible to move the endoscope and instruments at the same time, which limits the possible operation procedures.

Hand-free interfaces offer another solution to let a surgeon simultaneously control three instruments alone. Various systems have been developed for laparoscopic or otolaryngological surgery with a rigid endoscope controlled by head motion [11], eye gaze [12], verbal commands [13] or foot control [14]–[17]. Foot motion is a potentially reliable solution to control a third instrument to work together with hand-controlled instruments [18], [19]. Compared to other hand-free control strategies, this could provide similar control performance [20] and less interference than control derived from hand or eye movement. However, the foot-controlled systems currently used in robotic surgery mostly control the movement in a single Cartesian axis/joint at each time, which is less efficient and intuitive to control motion in multiple DoFs. For example, in the FREEDOM system [17] each joint is activated separately, so that controlling complex movements requires the combination of multiple foot gestures.

This paper presents a novel foot-controlled teleoperation robotic system for a flexible endoscope. Natural foot patterns are mapped to the movements of the endoscope using a dedicated interface. The robotic system can be integrated with standard gastrointestinal endoscopes and enables four-DoF motion control. The proposed system is evaluated in an experiment with ten participants, where the proposed system with foot teleoperation is compared with hand teleoperation and direct control of the endoscope.

II. ROBOTIC SYSTEM

The foot-controlled endoscopic system (shown in Figs.1a,b) is composed of the slave robotic endoscope and the master foot-controlled interface. The operator, seated comfortably, tele-controls the flexible endoscope with their right foot based on the camera view.

A. Master foot interface

The dedicated foot interface of [21], [22] was used as a master device to control the endoscope. The interface prototype with the operator's foot is shown in Fig. 1c. It consists

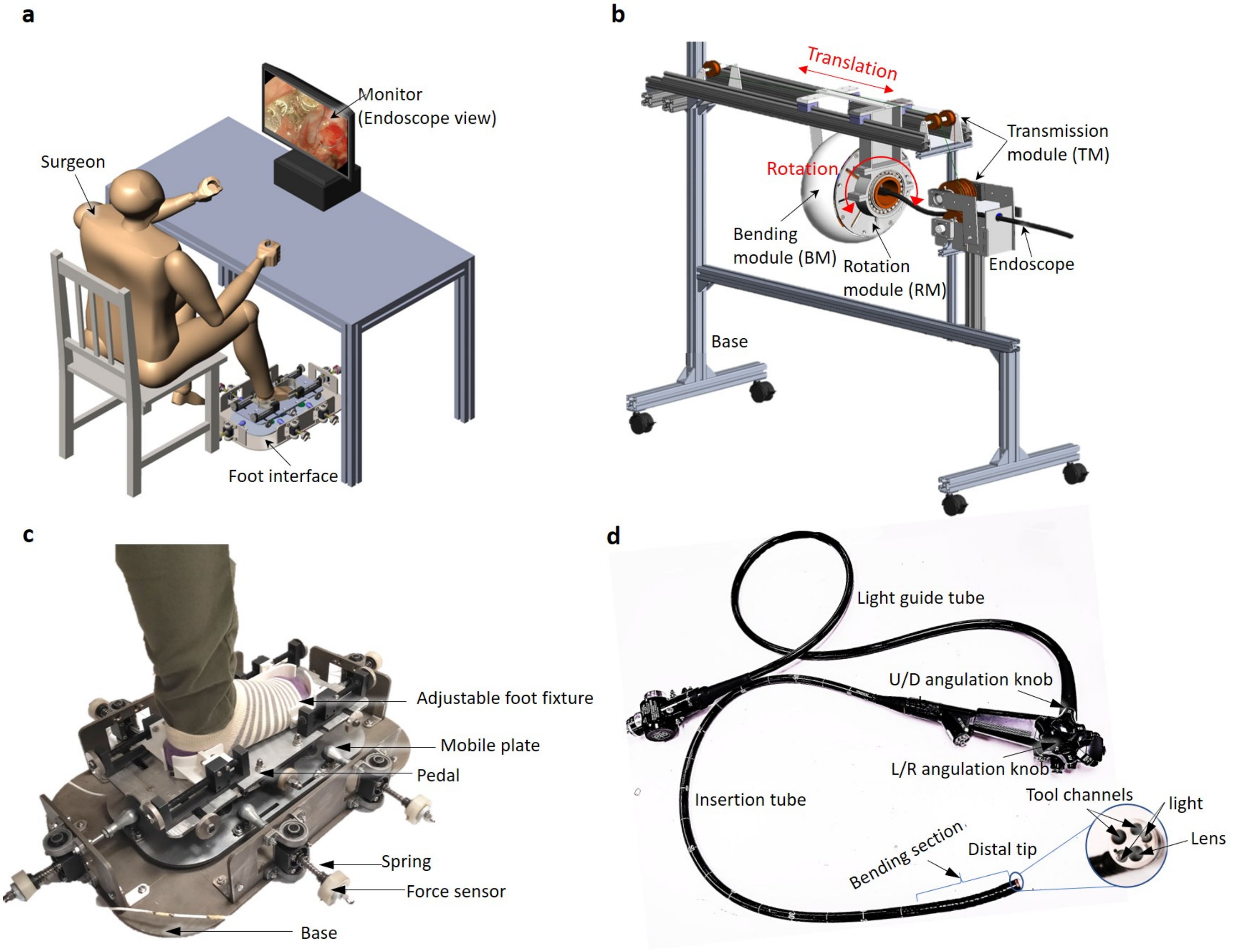

Fig. 1. Robotic endoscope teleoperation system: (a) Control console and operator; (b) Slave robotic endoscope system. (c) Foot interface prototype with foot. (d) Olympus gastrointestinal scope.

of a base, a mobile plate, a pedal with adjustable foot fixture and eight sets of springs and force sensors. The interface can collect four-DoF natural foot position and force signals. It is here integrated within the foot-controlled robotic endoscope system and tested to control the endoscope.

B. Foot-endoscope mapping

Motion signals from the foot act as references for the rotation of the proximal motors which drive the distal tip of the endoscope through cables. Four-DoF foot motion with the foot interface will control the corresponding movement of the endoscope: 1) Pressing/lifting the pedal activated by toe up/down rotation controls the up/down bending of the endoscope (Fig. 2a). 2) The left-right rotation of the pedal is linked with the left-right bending of the endoscope (Fig. 2b). Bending in multiple DoFs is allowed, e.g. lifting and rotating left of the pedal could lead to up-left bending of the endoscope. 3) The left-right swing of the pedal, activated by shank rotation around thigh, maps to the rotation of the endoscope (Fig. 2c). 4) The forward-backward movement of pedal is linked to same movement of the endoscope (Fig. 2d). The operator can imagine their toe as the tip of the endoscope and remote control the endoscope intuitively through isomorphic mapping.

In addition, the two bending DoFs can be commanded either using velocity or position control based on the practical application scenario. In position control mode, the foot positions are mapped to the endoscope's bending angles. The foot workspace corresponds to the bending workspace of the endoscope; In velocity control mode, the foot positions control the velocity of the endoscope. Once the endoscope reaches the position threshold of the movement, the output speed of the foot interface will change to zero in order to avoid safety issues. For the DoFs of translation and rotation of the endoscope, the foot positions are mapped to the velocity of the endoscope. The four-DoF movements of the foot to the corresponding movements of the endoscope in velocity control can be observed in supplementary video 1.

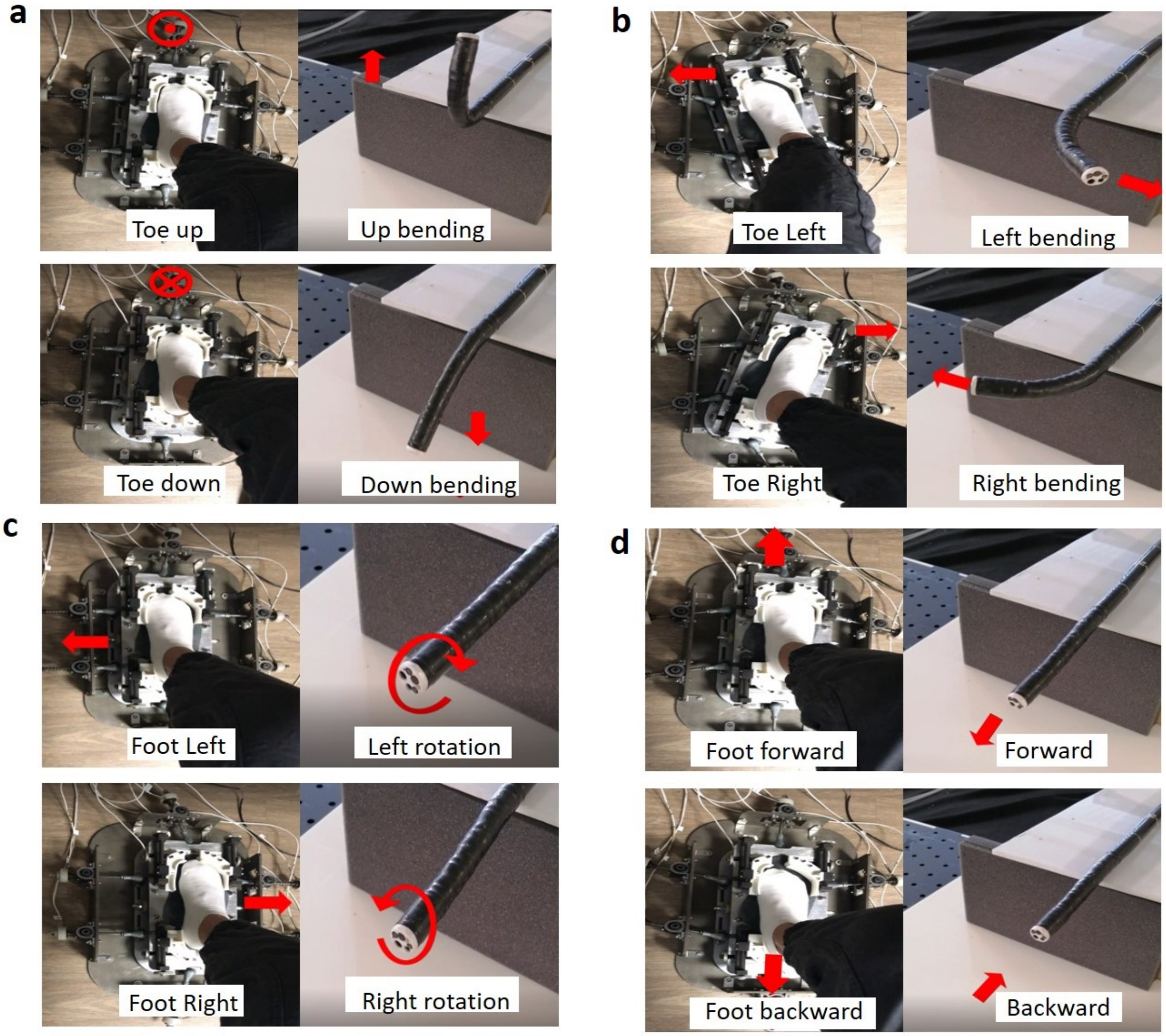

Fig. 2. Endoscope control in four DoFs with the foot interface. (Note that the left or right is defined based on the endoscopic vision rather than external vision.)

C. Slave robotic endoscope

The flexible endoscope used in this study is the standard gastrointestinal scope (GIF-2T160, Olympus Medical System Corporation, Tokyo, Japan), shown in Fig. 1d. It has a tube diameter of 12.6 mm and maximum insertion length of 103 mm, which is long enough to reach the surgical site of colon or stomach in gastrointestinal endoscopic surgery. This commercialized endoscope can be easily and quickly mounted on or dismounted from the robotic system without any modification.

The robotic endoscope (Fig. 1b in assembly view and Fig. 3 in exploded view) includes three modules motorizing the standard endoscope in four DoFs: 1) a bending module (BM) controlling the two-DoF bending of the distal tip; 2) a translation module (TM) executing the in/out DoF of the endoscope; and 3) a rotation module (RM) implementing the rolling DoF of the whole endoscope along the longitudinal axis.

1) Bending module: Fig. 3a presents the assembly of the BM; the right panel shows the exploded view of the connection parts to the endoscope. The claw shape knob connector mechanism are attached to the control knobs of the endoscope. Once the endoscope is connected, lifting up a tightening ring ㉒ can secure the knobs with connected shafts. Two motors with gears can drive the connected shaft and knobs through the gear transmission mechanism. The movement can be controlled in the two directions separately, or simultaneously.

2) Rotation module: The rotation module (Fig. 3b) can drive the tyre-shape BM and endoscope to rotate around endoscope's longitudinal axis. Weight block ⑯ (Fig. 3a) is added to BM to provide a counter moment to balance the rotation torque caused by ⑦, ⑨, ⑪ and ⑫ (Fig. 3a). The rotation is transmitted through pulley and cable when motor ㉖ rotates (Fig. 3b). The rotation motion and translation motion of the endoscope are decoupled. When the rotation motion is activated, the TM will loose the endoscope to allow its rotation.

3) Translation module: The structure of TM is shown in Fig. 3c. The endoscope can be easily passed through the four rollers by slightly lifting the L-shape plate ㉜. In addition, the

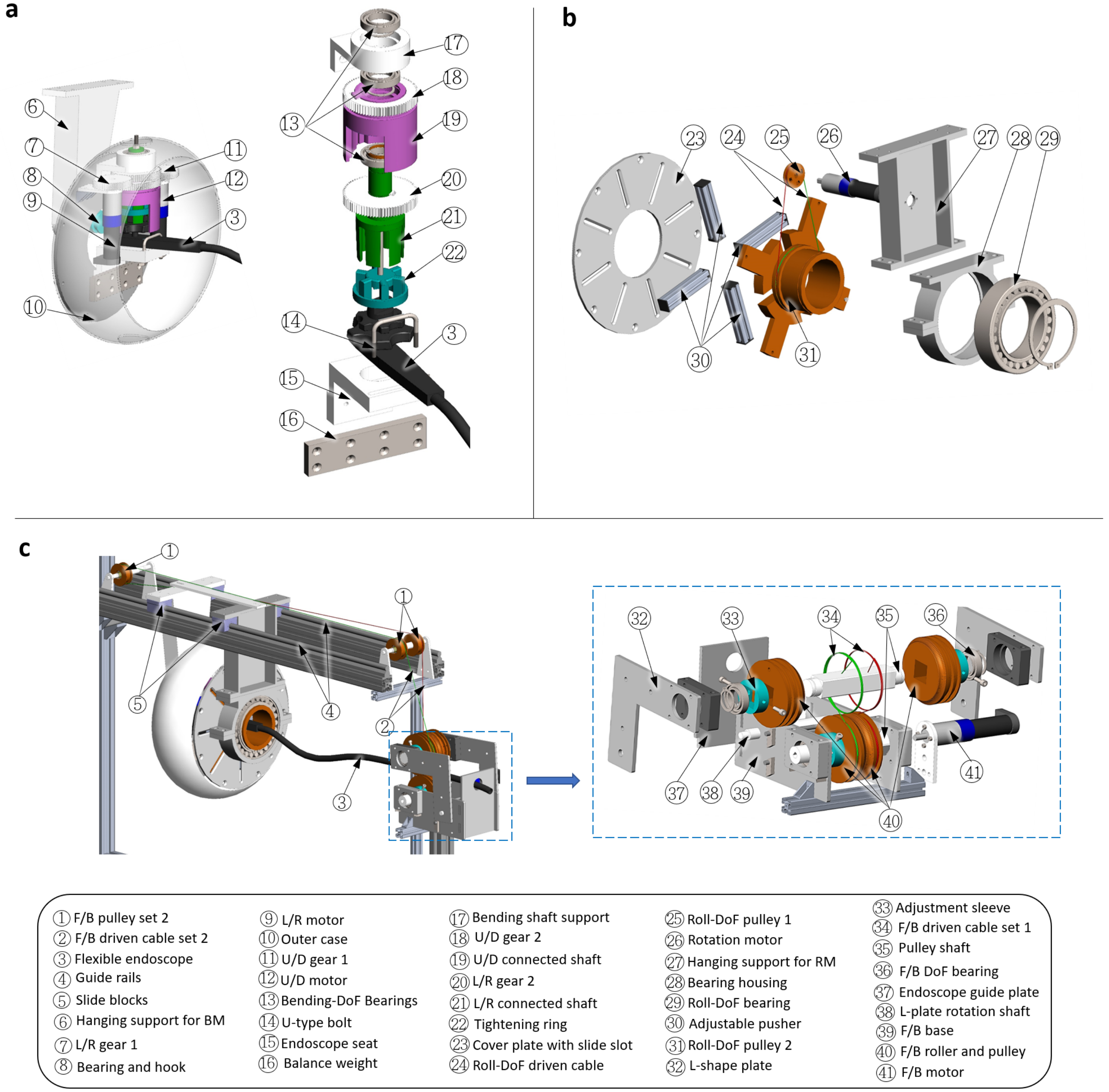

Fig. 3. Slave robotic endoscope system. Exploded view of bending module (a), rotation module (b) and translation module (c).

mechanism can fit the endoscope with different diameters by moving the width adjustment sleeves ㉝. The driven cables ㉞ are tightened after the assembly. The roller part is also a pulley with cables. Two sets of the cables ②, ㉞ are driven by the same motor forming a push-pull mechanism, which brings the whole endoscope, including the BM and RM, forward/backward together along the guided rails ④. This design can keep a consistent configuration of the endoscope to maintain the accumulated angle unchanged. This ensures the accurate control of the distal tip [23]. The current system range of 500 mm translation can be extended by using longer guided rails.

III. EXPERIMENT

The experiment was approved by the Institutional Review Board of Nanyang Technological University (IRB-2018-05-051). It was carried out by ten right handed and right footed subjects aged 29.3±3.8 years (with four females) without known impairment in foot or hand control.

The experiment was designed to evaluate the control of the endoscopic robotic system, where foot teleoperation was compared with direct control and hand teleoperation. In *direct*

TABLE I
POST EXPERIMENT QUESTIONNAIRE

Statement		Score					
1. The mapping between foot and robot movements is	very intuitive	1	2	3	4	5	not intuitive
2. General comfort was	very comfortable	1	2	3	4	5	very uncomfortable
3. Overall the operation was	easy	1	2	3	4	5	difficult to use
4. Mental effort required for operation was	low	1	2	3	4	5	high
5. Physical fatigue was	none	1	2	3	4	5	very high

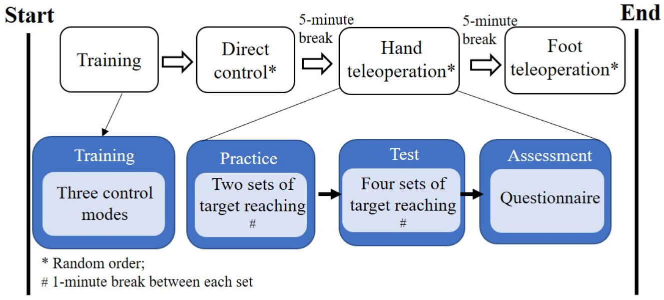

Fig. 4. Experimental flowchart.

control, the endoscopist manually controls the endoscope at the patient side using its built-in knobs while assisting the surgeon operating the robotic system. This is the conventional approach for maneuvering the flexible endoscope to perform diagnose or surgery, which is also used in endoscopic robotic systems MASTER [24], ViaCath [25]. *Hand teleoperation and foot teleoperation* both use a robotic system to move the endoscope remotely through a hand or foot interface, respectively. Hand teleoperation is the most common way to tele-operate robotic endoscope systems [10], [26], [27] while foot teleoperation is relatively new. The implementation of these three operation modes' implementation is described in more detail in Section III-A2.

A. *Test procedure*

The experimental protocol is illustrated in Fig. 4. After having signed a consent form, the participants attended a *training section* consisting of: (i) a demo on how to use the foot interface, hand interface and direct control to move the flexible endoscope; (ii) They were given 15 minutes to try each control mode for five minutes; (iii) They were informed of the task procedure.

Each participant performed six sets of operation in the *task section*. The first two sets was for practice and trial, where data was not recorded. The last four sets of operation were recorded as test data. There was a one-minute break between each set and five minutes break after one control mode to prevent fatigue. The *subjective assessment section* was conducted after the operation, i.e., each participant was asked to fill a questionnaire, as shown in Table I, in order to assess the mapping, operation comfort, ease of use and mental & physical effort for the three control schemes with a Likert scale from 1 to 5.

1) Experimental Task: In endoscopic surgery, the endoscope is a carrier with a camera providing both view and movement [28]. The navigation of the endoscope transports the surgical instruments to the target operation areas and facilitates their manipulation. An endoscope locomotion task under camera view was tested in the experiment (Fig. 5a). A red laser pointer was attached to the tip of the endoscope and its red projection point was shown in the endoscopic camera view, which provides the movement reference. Participants were asked to control the laser point to five circular targets (with radius 1 cm) located in the 3D space using visual feedback through the endoscopic camera. In each set of operations, the operator started from the initial position and moved sequentially from targets 1 to 5. The operation duration was recorded from the instant when the endoscope started to move, until when the last target was reached. Each operator was required to perform the task using the hand, foot teleoperation and direct control modes. The participants were randomly assigned to start with direct control, or with teleoperation using hand or foot. Within these teleoperation control modes, they randomly started with the hand or foot control.

2) Control schemes: The proposed foot teleoperation control scheme (Figs. 2, 5d) is compared with a hand teleoperation and direct control. Details of the foot teleoperation can be found in Section II-B. The hand teleoperation setup is the same as used in the foot teleoperation using the haptic interface (Omega.7, Force Dimension) replacing the foot interface (Fig. 5c). The four-DoF motion of the hands are mapped to the motion of the endoscope as follows: Left/right and up/down translations of the hand control the left/right and up/down bending of the endoscope, respectively; The forward-backward hand translation controls the in/out motion of the endoscope, and the forearm rotation controls the self rotation of the endoscope.

For both hand and foot teleoperation, the two bending DoFs of the endoscope are position-controlled, providing an intuitive and accurate mapping. As the motion range in translation (≥ 50 cm) and rotation (360^o) on the robot side are large compared to the range of master interfaces, using position control would require frequent clutching operation. Thus velocity control is used for the translation and rotation DoFs in order to avoid the workspace limits and uncomfortable postures. In direct control (Fig. 5b), the operator uses one hand to grab the control section of the endoscope and uses the fingers of their hand to rotate two control knobs. Rotating the bottom or upper knob control the up/down, left/right bending DoFs of the endoscope respectively. The other hand of the operator should hold the distal end of the endoscope (about 15-20 cm from the tip) [29]. The translation or rotation DoF requires two hands to deliver or twist the whole body of the endoscope. The

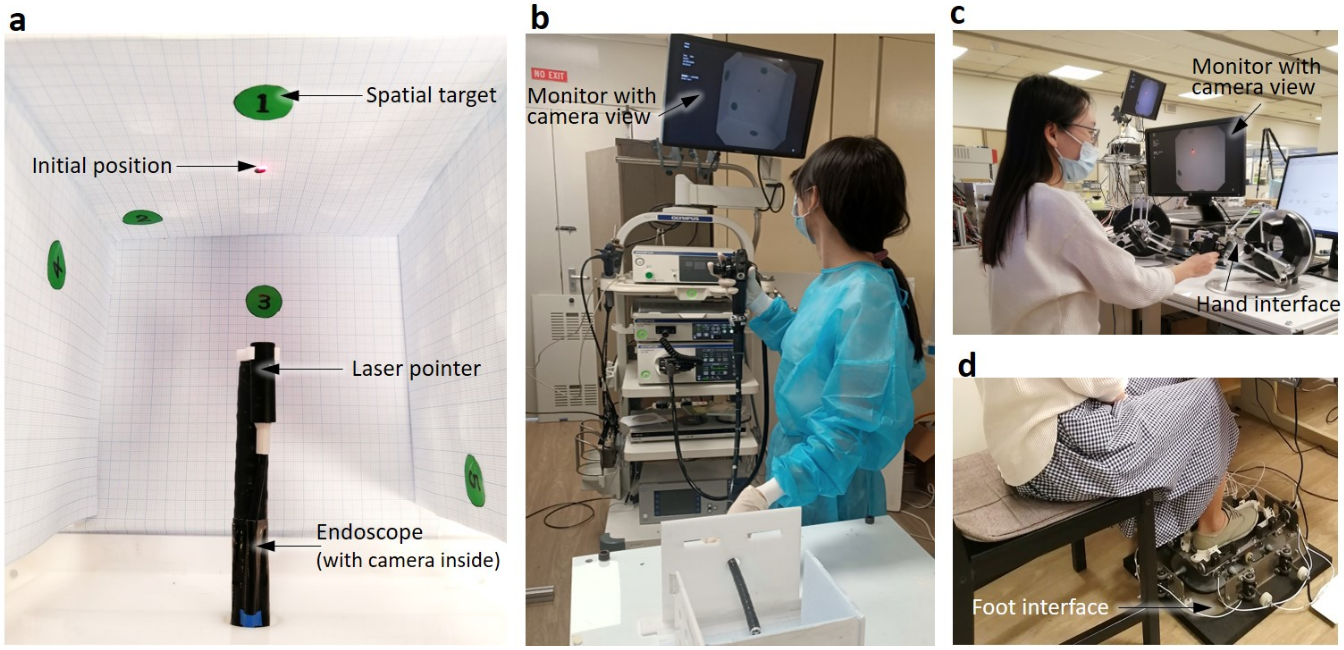

Fig. 5. Experimental setup. (a) Endoscope and spatial targets. (b) Direct control. (c) Hand teleoperation. (d) Foot teleoperation.

participants operate through the same endoscopic camera view for all three control modes, and are not allowed to look at the endoscope tip and targets directly.

B. Three instruments' operation demo

In endoscopic surgery, the two flexible instruments, passing through the tool channels inside or attached to the endoscope, can perform dexterous manipulation; the endoscope can enlarge the workspace of the operation, bringing instruments to the target area. The proposed foot controlled robotic endoscope enables the surgeon to operate two surgical instruments using their hands without disruption and therefore carry out endoscopic surgery involving three tools. Supplementary video 2 shows a solo surgical operation on porcine tissue carried out with the endoscopic robotic system. In this video, an operator uses the foot-controlled robotic endoscope system to remote control the flexible endoscope, and two hand haptic interfaces to teleoperate two robotic instruments to perform cauterising cutting.

IV. RESULTS

A. Operation efficiency

The resulting operation time is shown in Fig. 6. This data was normally distributed for each trials' set and control scheme, as assessed by Shapiro-Wilk's test ($p>0.09$). A two-way repeated measures ANOVA was conducted to determine the effect of different control schemes and trials' sets on the operation time. No statistically significant interaction effect was found between the control scheme and trials' set parameters, F(2.15,19.39) = 0.61, p = 0.56. Participants exhibited relatively consistent performance after two sets of practice in all three control modes (Fig. 6a). There was no statistically significant main effect of the four sets on the operation time, F(3,27) = 2.08, p = 0.12. However, as shown in Fig. 6b, the operation time did depend on the control scheme F(2,18) = 26.72, $p < 0.001$. A post hoc analysis (with Bonferroni adjustment) then revealed that the completion time decreased from using direct control (80.7±7.6 s) to hand teleoperation (31.1±1.8 s), ($p < 0.001$), from direct control to foot teleoperation (48.6±4.1 s) (p = 0.011), and from foot teleoperation to hand teleoperation (p = 0.005).

B. Subjective assessment

Fig. 7 illustrates the average responses (and the standard deviation) of ten participants to the questionnaires of Table I. The rating results were not normally distributed ($p <0.014$), and a Friedman test was run to analyze how the control scheme affects the subjective rating. The control scheme had a significant effect on the rating of *intuitiveness*, $\chi^2(2) = 13.515$, p = 0.001. Post hoc analysis revealed that direct control (Median(Mdn) = 4) was felt non-intuitive, in contrast to hand (Mdn = 1, p = 0.005) or foot (Mdn = 1.5, p = 0.03) teleoperation of the robotic system. Instead, subjects found hand and foot teleoperation similarly intuitive (p = 0.9).

Significant effects were also found for the other criteria of *comfort* ($\chi^2(2) = 16.722$, $p < 0.001$), *difficulty* ($\chi^2(2) = 15.600$, $p < 0.001$), *mental effort* ($\chi^2(2) = 8.061$, $p = 0.018$), and *physical fatigue* ($\chi^2(2) = 16.222$, $p < 0.001$). The participants generally found hand teleoperation superior in all those aspects to direct control ($p < 0.03$). Foot teleoperation was felt to provide more comfort (p = 0.02) and less fatigue (p = 0.04) than direct control, but no significant difference in difficulty (p = 0.28) and mental effort (p = 0.44). Similar to the result of intuitiveness, the participants felt that the foot teleoperation did not increase the difficulty of the operation,

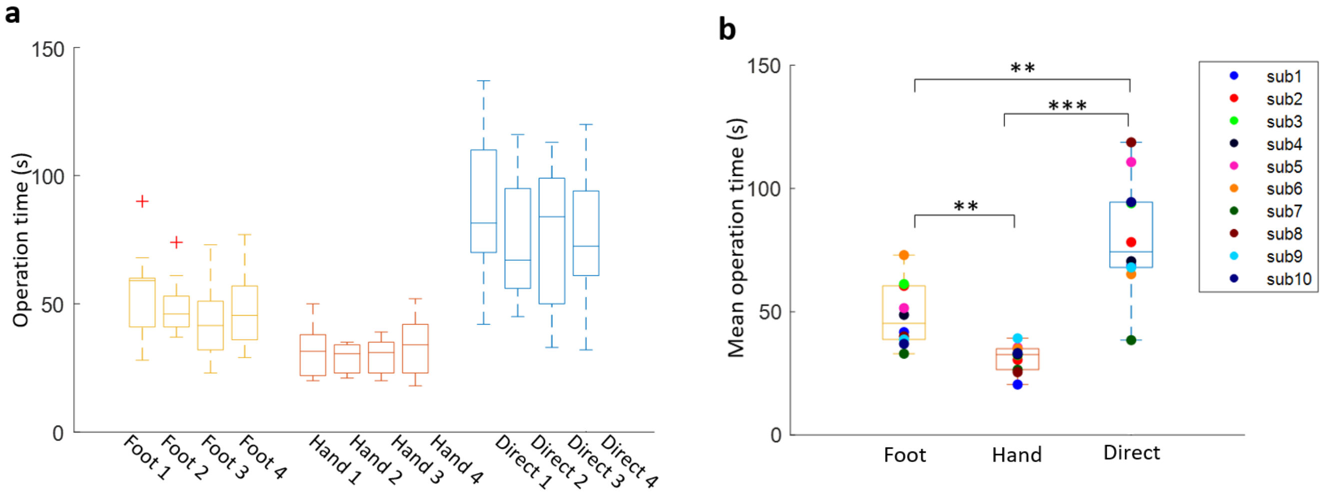

Fig. 6. Operation time with the three control modes. (a) Mean operation time over the four trials; (b) Evolution of operation time in the four trials. *: statistically significant effects at *p<0.05, ** p<0.01, *** p<0.001.

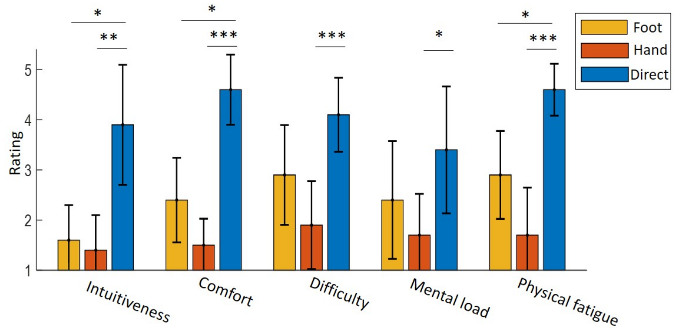

Fig. 7. Subjective assessment. * p<0.05, ** p<0.01, *** p<0.001.

or bring more physical or mental effort, or discomfort, when compared to hand teleoperation (p = 0.13 for difficulty, p = 0.35 for physical fatigue, p = 0.79 for mental effort, p = 0.66 for comfort).

V. DISCUSSION

This paper presented the design and evaluation of a novel foot-controlled robotic endoscope system. The teleoperation system provides four-DoF control of a flexible endoscope. Natural movements of the user's foot are captured by the foot interface and then used to tele-manipulate the endoscope. The system can be easily integrated with the commercial endoscope. The experimental study validated the design and showed the feasibility of the novel foot-controlled robotic system. The participants could tele-manipulate the endoscope intuitively with their right foot and reach the target area without difficulty. The foot teleoperation is more efficient and intuitive than conventional direct control. The average completion time per set was 43.6 - 54.7 s for the foot teleoperation and 73.0 - 89.2 s for the direct control, i.e. the time is reduced by about 40% with the proposed system. Furthermore, the participants felt that less physical effort is required to operate the robotic endoscope using the foot than directly controlling it, and that foot teleoperation is more comfortable.

In our experiment, hand teleoperation needed less operation time than foot teleoperation, which is expected as the hands are the limbs normally used to control objects in space. However, using two hands to control three surgical tools in endoscopic surgery may not be that efficient. For instance, when adjusting the camera view with some camera positioners [30], the surgeon needs to release the current instruments, disengage the locking mechanism, operate the third instrument, reengage the locking mechanism, pick up previous instruments, and resume the procedure. Some studies [31], [32] also reported that in the Da Vinci surgical system the swapping procedure using pedal clutching may disrupt the surgical flow and lead to errors or extended operation. In contrast, using the foot to operate a third tool does not disrupt the hands operation. The behaviour study in [33] also suggests that three-handed simultaneous positioning is preferred to - and more efficient than - bimanual operation.

The developed robotic endoscope system provides unique novel features relative to existing systems in endoscopic surgery: (i) natural foot gestures are used to control the endoscope based on an isomorphic mapping which is intuitive and easy to learn; (ii) using the foot interface enable the hands to control additional instruments and makes it possible to carry out operations requiring simultaneous operation of three tools; (iii) can be integrated with a two-handed control system in a modular design. The successful foot teleoperation experiments conducted by ten participants without surgical experience/bias shows the effectiveness of the foot-controlled endoscopic robotic system. It will be necessary to complete this feasibility study of the endoscope control with the foot interface with systematic experiments to test the trimanual control of professional surgeons.

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