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A three-limb teleoperated robotic system with foot control for flexible endoscopic surgery

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Abstract

Flexible endoscopy requires a lot of skill to manipulate both the endoscope and the associated instruments. In most robotic flexible endoscopic systems, the endoscope and instruments are controlled separately by two operators, which may result in communication errors and inefficient operation. Our solution is to enable the surgeon to control both the endoscope and the instruments. Here, we present a novel teleoperation robotic endoscopic system commanded by one operator using the continuous and simultaneous movements of their two hands and one foot. This 13-degree-of-freedom (DoF) system integrates a foot-controlled robotic flexible endoscope and two hand-controlled robotic endoscopic instruments, a robotic grasper and a robotic cauterizing hook. A dedicated foot-interface transfers the natural foot movements to the 4-DoF movements of the endoscope while two other commercial hand interfaces map the movements of the two hands to the two instruments individually. An ex-vivo experiment was carried out by six subjects without surgical experience, where the simultaneous control with foot and hands was compared with a sequential clutch-based hand control. The participants could successfully teleoperate the endoscope and the two instruments to cut the tissues at scattered target areas in a porcine stomach. Foot control yielded 43.7% faster task completion and required less mental effort as compared to the clutch-based hand control scheme, which proves the concept of three-limb tele-operation surgery and the developed flexible endoscopic system.

Keywords— Three-tools operation, foot control, teleoperation, endoscope manipulation, robot-assisted surgery.

1 Introduction

Compared to conventional open surgery, minimally invasive surgery (MIS) offers many benefits to patients, such as reduced trauma, less blood loss and faster recovery.¹ In conventional MIS laparoscopic procedures, rigid long-shaft instruments are used to access the surgical area inside the patient's body and thus incisions have to be made on the patient's body to gain access. To avoid skin incisions and promote faster recovery, natural orifice transluminal endoscopic surgery (NOTES) has been proposed. In NOTES, the surgeon can access abdominal organs using flexible tools through the natural orifice such as anus, mouth, and vagina, avoiding skin incisions on the body.^{2,3} However, conducting NOTES or other endoscopic therapeutical procedures such as Endoscopic Mucosal Resection (EMR) or Endoscopic Submucosal Dissection (ESD)⁴ is challenging because (1) the endoscopic instruments are not steerable, (2) countertraction of tissue is not possible, (3) the procedures are highly dependent on the steering motion of the endoscope while steering the endoscope is not intuitive.

Therefore, robotic technologies have been proposed for these procedures.^{5,6} The surgeon can sit behind the master console, intuitively controlling two steerable robotic instruments which can easily reach targets and provide tissue countertraction. Multiple robotic systems have also been developed for flexible endoscopic surgery enabling intuitive operation of endoscope or endoscopic instruments. For example, robotic-assisted flexible endoscope (RAFE),⁷ motorized endoscope,⁸ and *i²* snake robot⁹ facilitate the endoscope operation through teleoperation with one or two hands interfaces. The MASTER¹⁰ and ViaCath¹¹ robotic systems provide intuitive bi-manual teleoperation of two endoscopic instruments. However these platforms still require an endoscopist to assist the surgeon to control the endoscope when the surgeon is manipulating the two instruments, which is not efficient and may cause communication and errors, especially for novice assistant or new team.^{12,13}

The efficiency may be improved and communication errors could be eliminated if the surgeon can control all the involved tools (the endoscope and the two instruments). There are a few complete robotic systems in flexible endoscopy which include three or more robotic arms controlled by one surgeon. Table 1 lists representative examples of such systems with a robotic endoscope control mechanism.^{7,14–18} Among them, the FLEX,¹⁷ EOR¹⁸ and RAFE⁷ systems require manual control of the instruments. The following three approaches have been proposed to help a surgeon

control both endoscope and instruments:

- *Hand-independent interface control*, which is similar to approaches used for rigid endoscopes, the head, foot, finger or voice is used to command the endoscope. The latest version of the STRAS system¹⁵ includes two small four-way finger joysticks on the hand controllers to operate the endoscope using two thumbs of both hands. Each joystick can control the two-DoF motion of the endoscope.
- *Separate interface hand control*. In the Medrobotics FLEX¹⁷ system, the operator firstly navigates the endoscope to the target area using a joystick and then switches to the manual instruments.
- *Clutch-based hand control*, with clutch buttons or pedals in the master console to activate the swapping to the third tool. For robotic systems such as K-FLEX,¹⁶ the operator uses the same hand interface to control a surgical tool or a flexible overtube, switched by a foot clutch.

Table 1: Robotic systems for flexible endoscopic surgery

System	Endoscope control	Tools control	Endoscope DoF	System DoF	Application
RAFE ⁷	Hand, Handle	Manual	4	-	gastrointestinal tract surgery
STRAS ¹⁵	Thumbs, Two four-way switches	Robotic	4	11	gastrointestinal tract surgery
K-FLEX ¹⁶	Hand, Handle (swap by foot clutch)	Robotic	4	14	gastrointestinal tract surgery
FLEX ¹⁷	Hand, Joystick-like controller	Manual	-	-	ENT surgery
EOR ¹⁸	Hand, Handle and mini-joystick	N/A	4	-	gastrointestinal tract surgery
Proposed system	Foot, Foot interface	Robotic	4	13	gastrointestinal tract surgery

Using a separate hand interface or a hand clutch require sequential control, which may not be intuitive or efficient.¹⁹ The necessity to change tool may disrupt the control as the surgeon needs to

pause the current operation, swap to operate the third tool and resume the previous operation.^{20,21} In addition, existing hand-independent interfaces in robotic surgery using the head,²² eye²³ or finger^{15,24} control are not completely independent from the hands operation. Foot control provides a good modality for the input when the hands are occupied by their current tasks^{25,26} with natural mapping to locomotion tasks and manipulation tasks.²⁷ However the foot interfaces used so far in robotic surgery are not conceived to simultaneously control three tools. They either require multiple foot gestures²⁸ to activate one joint at a time, or include multiple buttons^{29,30} needing visual check of the foot positioning.

Our goal is to develop a robotic system that enables the surgeon to control the endoscope and two surgical instruments simultaneously and intuitively. The developed system consists of a foot-controlled robotic endoscope and a two-hand-controlled robotic platform with two instruments. In our system, the four-DoF natural foot gestures map to the movement of the endoscope and cooperate intuitively with the hand manipulation. This robotic system enables one operator to control the 13 DoFs of the endoscope (four DoFs), the grasper (five DoFs) and the cauterizing hook (four DoFs). This paper *i*) presents the novel teleoperated robotic system with foot control for flexible endoscopic surgery enabling one operator to control three surgical tools, *ii*) tests the feasibility and intuitiveness of the three-hand surgery with naive users, and *iii*) compares it with traditional hand-clutch control.

2 Material and methods

2.1 System

The three-limb endoscopic teleoperated robotic system is shown in Fig. 1. At the master site, two commercial hand interfaces are used to collect the motion signals of the hands, and a foot interface is used to capture the foot gestures of the surgeon. The slave system consists of three robotic tools, i.e., an endoscope and two surgical instruments passing through the external tool channels which are attached to the endoscope. With this master-slave architecture, the motions of the surgeon's hands and foot are mapped to those of the slave arms. The design, setup and control aim to increase the transparency and intuitiveness between the master and slave control.

Figure 1: Overview of the three-limb teleoperated robotic system. (a) Master console for the surgeon including two hand interfaces, one foot interface and a visual display. (b) Slave surgical robot systems for the endoscope and the two endoscopic instruments.

2.1.1 Master Interfaces

Hand interface Two Force Dimension Omega 7 haptic interfaces (Fig. 2a) are used to remotely control the robotic instruments. Each interface can control six-DoF movements and one-DoF grasping. Four DoFs of the hand motions are selected to control each slave tool.

Foot interface The foot interface shown in Fig. 2b was designed to control the flexible endoscope.³¹ It is a hybrid parallel-serial structure consisting of a base, a mobile plate, a pedal with adjustable foot fixture and eight sets of serial elastic sensing modules of springs and load cells. This interface has been evaluated in a teleoperation system controlling an industrial robot.³² The forces applied by the operator's foot is transmitted through springs and recorded by the force sensors. The set of multiple springs provide haptic feedback for the position that is independent of the subject's vision. When the operator finishes movements and releases the pedal, the interface returns to the home position automatically, providing positioning assistance and a resting posture for the foot. During the operation, the operator first steps the foot on the pedal and adjusts the four foot-shape blocks to fit their foot size. The pedal supports the leg against gravity thus minimizing

Figure 2: Master interfaces with (a) hand interface and (b) foot interface. (c) Robotic instruments of grasper (lower) and mono-polar cauterizing hook (upper). (d) Flexible endoscope.

fatigue.

2.1.2 Slave robotic system

Robotic instruments In the current implementation, the two robotic instruments are a grasper (lower) and a monopolar cauterizing hook (upper) as shown in Fig.2c. They can be changed to other surgical instruments, such as a suturing device.³³ Each robotic arm can provide four-DoF motion (the grasper has an additional grasping motion). The bending and grasping DoFs are driven by a tendon-sheath mechanism, where each DoF is controlled by two antagonistical tendon-sheath mechanisms and motors. At the proximal end, pretension is applied to each tendon to reduce the effect of backlash and slacking. Load cells are used to monitor the proximal tension

force for every tendon. The translation and rotation DoFs are actuated by a motorized linear slider and a rotary motor at the proximal side, respectively. The robotic instruments pass through the external tool channels that are attached to the endoscope. The diameter of the instrument is 4.2 mm. The internal and external diameters of the tool channel are 5 mm and 6 mm respectively. The maximum length of the cross section of the endoscope with instruments is about 17 mm, which is in the appropriate size range of endoscopic multiple-tool platforms.⁵

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. 2d. 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. The endoscope consists of a bending section (including the distal tip), insertion tube, and the control section.

The robotic system is based on a modular design, which can be integrated with the standard flexible endoscope and motorized in four DoFs. The two motors connecting with the knobs located on the control section of the endoscope through gear transmission can drive the two-DoF of up/down (U/D) and left/right (L/R) angulation of the bending section. The in/out translation along the longitudinal axis can move with a range of 500 mm translation. The rolling of the endoscope is driven by rotating the whole endoscope body. The rolling DoF and translation DoF are decoupled. When the rotation is activated, the translation mechanism loosens the endoscope to allow its rotation. In addition, the mechanism can fit endoscopes with different diameters from 10 to 20mm.

2.1.3 Control mapping

Left hand movements control the five DoFs of the surgical grasper (Figs. 2a,c), the right hand controls the four DoFs of the surgical hook, and the foot interface the four DoFs of the flexible endoscope. In the initial position, the two instruments extend out about 60 mm from the tip of the endoscope. They can be withdrawn a maximum of 40 mm. Each bending joint can rotate $[-83^\circ, 83^\circ]$. Each of the delicate surgical arms has a cylindrical workspace with a cross-sectional diameter of 25 mm. The endoscope has a larger workspace with a cross-sectional diameter of 160 mm which can significantly increase the workspace of the instruments.

Figure 3: Motion mapping between the foot and endoscope.

The approach of the left hand controlling the grasper is described here, and the related variables are defined in Figs. 2a,c. The grasper's translation (relative to the endoscope camera) is controlled by the left hand forward/backward movement according to $y_i = \alpha_1 x_h$, $\alpha_1 > 0$. The grasper's L/R steering motions are controlled by the lateral hand movement as $\phi_i = \alpha_2 y_h$, $\alpha_2 > 0$, the U/D bending by the vertical hand movement as $\theta_i = \alpha_3 z_h$, $\alpha_3 > 0$. The grasper's rotation is controlled in velocity by the hand/forearm rotation according to $\gamma_i = \alpha_4 \dot{\gamma}_h$, $\alpha_4 > 0$. As forearm rotation has a very limited range of comfortable postures thus velocity control is more appropriate. The grasper's opening/closing is controlled by the hand gripper mechanism angle. The hook, with a similar design, is controlled in the same way. Note that the hook does not have an opening/closing

jaw.

The four DoFs of the endoscope are controlled in velocity by foot motions through the foot interface as shown in Fig. 3. The endoscope in/out y_e is controlled by the foot forward/backward movement y_f according to $y_e = \beta_1 \int y_f$, $\beta_1 > 0$. The endoscope rotation γ_e is controlled by the foot lateral translation with $\gamma_e = \beta_2 \int x_f$, $\beta_2 > 0$. The foot flexion/extension controls the endoscope up/down movement as $\theta_e = \beta_3 \int \theta_f$, $\beta_3 > 0$, and the foot rotation the endoscope left/right bending with $\phi_e = \beta_4 \int \phi_f$, $\beta_4 > 0$. This mapping is intuitive as the selected movements of the foot are similar to the corresponding movements of the endoscope. For instance, the forefoot rotation around the ankle, can be intuitively regarded as the bending tip of the endoscope. The operator can take the foot and shank as the endoscope for metaphor. The foot can remote control the endoscope easily through isomorphic mapping.

2.2 Experiments

To examine the system's performance, we firstly investigated the inherent motion hysteresis of the instruments and endoscope in the bending DoFs with a tendon-driven mechanisms. Six subjects were recruited for the experimental study within research staffs from the Engineering Faculty, Nanyang Technological University. These subjects aged 30.5 ± 2.9 year old were all right handed and footed, have no known sensorimotor impairment, and the group has 2 females. The same subjects also conducted an ex-vivo test with an surgical cutting task in order to assess the system for three-hand operation, and compare it with hand clutch control. The supplementary video shows a surgical task operation carried out by one of the participants.

2.2.1 Robotic system motion control study

Tendon-driven mechanisms have the inherent drawback of backlash due to the slacking and elongation of the tendons, friction at the joint, etc.^{34–36} The robotic grasper and hook thus used an antagonistic system of cables for each bending DoF with adjustable pretension to reduce the backlash. In contrast, the endoscope used in the system has low, non-adjustable pretension which leads to larger backlash. Motion studies of robotic instruments and endoscope in two bending

Figure 4: Robotic instrument motion study. (a) motion joints (b) set up. Endoscope motion study (c) set up and (d) angle calculation.

DoFs were conducted to study the respective backlash and deadzone.

Robotic instrument motion study We have studied the proximal-distal motion behavior of tendon-sheath driven instruments for both pitch and yaw movements (Fig. 4a). When the operator uses the Omega 7 haptic device to manipulate the surgical tools, their movements are converted from distance into angles and then sent to the motor (desired proximal angle). The motor encoder then feed back the actual proximal angle. An encoder is attached to the tool's joint to record the actual distal angle (Fig. 4b). In the test, an operator at the master side was asked to move the hand controller back and forth to control the distal joint of the instrument in seven cycles. The signals of the hand controller were first transmitted to the proximal end motors of the slave robot and then passed to the distal end tool joint through 2.5 meters' long tendon-sheath mechanisms. The motion study result of instrument and endoscope is shown in Section 3.1.

Robotic endoscope motion study A motion study of the robotic endoscope is also conducted using the two bending DoFs. The test setup is shown in Fig. 4c. Ten yellow markers in a line with 6 mm diameter and 10 mm spacing were attached to the upper surface of the endoscope bending section. The motion of the ten yellow markers was tracked a 2D camera and saved at a sampling rate of 30 Hz. The camera was calibrated before the test using the checkerboard to correct the lens' distortion and identify the camera parameters. During testing, the camera was located on the top of the endoscope's bending section, recording the motion of the yellow markers and the status of the LED indicator light (for synchronization purposes). After the test, the video was analyzed (offline) to compute the planar position of ten marker points using a color marker based object tracking method by thresholding the color channels. The center points of the markers were then extracted and aligned at the initial static position. Eighth to ten markers away from the endoscope tip shows almost constant position during the test and thus the position of the eighth marker is regarded as the bending origin. The bending angle of the endoscope could be calculated through the coordinates of the first and eight markers (Fig. 4d), with $2 \arctan(\Delta x / \Delta y)$.

A LED indicator light (Fig. 4c) was located in the camera's image. This was used to synchronize the data of the proximal end motor and distal end endoscope tip. The light was turned off at the beginning. It was turned on when the motion command was sent to the proximal motor and turned off again when the proximal motor stopped. The light-up period of the indicator can be identified from the video. Thus, the motion data of the proximal motor and the distal tip of the endoscope were synchronized by using the signal of the indicator light.

2.2.2 Ex-vivo test

The six subjects described above performed a surgical point cutting task. Two control modes for three-hand operation, foot & hands control and hand clutch control, are compared in this test.

Experimental procedure The participants firstly attended a *training section* consisting of a demo on how to use the foot interface, hand clutch and hand interface followed by an individual practice of 20 minutes, after which they were informed about the task procedure. The participants were randomly assigned to start with one of the two control modes. Ten minutes were given for

a *practice section* to conduct a trial operation. After completing four sets of operations with one control mode in the *task section*, the participants were asked to practice and run another four sets of operations using another control mode. To prevent fatigue, there were 1-minute breaks between each set and a 5-minute break interval between the two control modes. The *subjective assessment section* was conducted after the experiment was completed, i.e., each participant was asked to fill a questionnaire in order to assess the mental effort, physical effort, operation efficiency, easiness and comfort for the tests with a Likert scale from 1 to 5. They were also asked to choose their personal preference among the two control modes and specify their reasoning (Table. 2).

Table 2: Subjective assessment questionnaire

Statement		Score					
1. The mental effort required for operation was	low	1	2	3	4	5	high
2. The physical effort required for operation was	low	1	2	3	4	5	high
3. The operation mode is	not efficient	1	2	3	4	5	very efficient
4. General comfort was	very uncomfortable	1	2	3	4	5	very comfortable
5. Overall the system was	difficult	1	2	3	4	5	easy to use
6. In general, which control modes do you prefer? Why? Please specify your reason(s)							

Foot & hands control See Section 2.1.3.

Hand clutch control The system also enabled a hand clutch control mode. In the hand clutch control mode, the endoscope and one tool are controlled by the same hand interface, swapping by clutch buttons. There are two clutch buttons attached to the handle of the hand interface, which can be easily pressed by the middle and ring fingers (Fig. 5a). Once the upper button is pressed, the hand interface will control the endoscope, and when the lower button is pressed, the interface will swap to control the surgical tool. The hand interface is set to control the endoscope at the initial state. Before commencing the task, participants are allowed to choose either their left or right hand interface to control the third tool.

The conditions of the hand clutch control are set to be the same with the foot control: translations in x_h, y_h, z_h, γ_h control in/out translation, L/R bending, U/D bending and rotation DoFs of

Table 3: Parameters of using foot or hand controlling the endoscope.

Hand			Foot			Endoscope	
DoF	Movement	Zero band	DoF	Movement	Zero band	DoF	Velocity
x_h	$[-50,50]\text{mm}$	$[-10,10]\text{mm}$	y_f	$[-20,20]\text{mm}$	$[-6,6]\text{mm}$	y_e	$[-20,20]\text{mm/s}$
y_h	$[-80,80]\text{mm}$	$[-16,-16]\text{mm}$	ϕ_f	$[-12.5,12.5]^\circ$	$[-4,4]^\circ$	ϕ_e	$[-20,20]^\circ/s$
z_h	$[-60,60]\text{mm}$	$[-12,12]\text{mm}$	θ_f	$[-10,10]^\circ$	$[-3,3]^\circ$	θ_e	$[-20,20]^\circ/s$
γ_h	$[-90,90]^\circ$	$[-27,27]^\circ$	x_f	$[-20,20]\text{mm}$	$[-6,6]\text{mm}$	γ_e	$[-20,20]^\circ/s$

the endoscope respectively. An outward-going linear increasing force feedback from -2 N to 2 N are provided to the hands, setting a automatic home position with minimal resistance force at middle position. The motion ranges of hand or foot are mapping to the same velocity range of the endoscope. All the movements and force feedback are set within a comfortable ranges. The parameters used for the foot and hand control as well as of the endoscope are summarized in Table 3.

Setup and surgical task The experimental setup is shown in Figs. 5. Fig. 5a,b depicts the master console for the operator including monitor with camera view, two hand interfaces, the foot interface and foot switches. The foot switches are used to activate monopolar option of Erbe electrosurgical unit. Which is commonly used in electrosurgery to cut the target tissue and/or coagulate bleeding. The operator uses two hands holding the hand controllers, one foot controlling the foot interface and another foot pressing the monopolar foot switches. The slave robotic systems and endoscopy image and lighting system are shown in Fig. 5c.

A pseudo surgical task was used to test the system with three hand control. Surgical procedures such as Endoscopic Submucosal Dissection (ESD) are challenging to carry out even for professional endoscopists, who require years of training to perform it skillfully.^{37,38} Therefore, to test the system and three hand operation with naive subjects, we selected as a simplified task the point cutting and marking at the specified areas using the electrosurgical unit instrument. This is part of the ESD procedures, e.g. marking, precutting or hemostasis etc.³⁹ The operators were asked to cut the tissue at four targets (e.g., locations) one by one from right to left. Cutting was defined as touching the tissue using the cauterizing hook knife. As shown in Fig. 5d, the porcine stomach weighing 0.6 kg was fixed on a $150 \times 150 \text{ mm}^2$ inclined surface with a 45° slope. The four

Figure 5: Ex-vivo test setup. (a) Master console. (b) Operator controls the master system. (c) Slave robotic system and surgical devices. (d) Robotic surgical instruments and working tissue.

targets located spatially (in the zone of $100 \times 50 \times 50 \text{ mm}^3$) on the tissue marked by blue color dye, inclusive of two exposed and two covered targets. The exposed target was marked as circular zone with 8 mm diameter; the covered target had an incision width about 15mm in length, the marked area was inside the incision and cannot be reached by only lifting up the covered tissue. One set of operation is complete when all four targets are successfully reached and cut. The completion time was from the start of the endoscope movement to its stop when the final target is cut. The result of the ex-vivo test is shown in Section 3.2.

3 Results

Figure 6: Motion control of hands, proximal motor and distal tool in DoFs of (a) L/R bending and (c) U/D bending. Motion hysteresis profiles of the instrument in (b) L/R bending and (d) U/D bending. Motion hysteresis profiles of the endoscope in (e) L/R direction and (f) U/D direction.

3.1 Instrument and endoscope motion profiles

Figs. 6a,c show the practical input-output motion behavior of the instruments for both pitch and yaw motions. The motion is affected by hysteresis caused by the friction and tendon elongation of the flexible tendon-sheath mechanisms. The effect of hysteresis on the proximal angle and actual distal angle for both yaw and pitch motions are shown in Fig. 6 b,d.

Figs. 6e,f depict the relationship between proximal motor position and distal bending angle

for the endoscope when actuating each DoF individually. The hysteresis profile is similar as in previous studies.^{14,40} The proximal motor rotated bidirectionally (recorded as positive to negative angles) for two cycles in each level. There are non-linear areas, especially in the middle of the profiles (about $\pm 20\text{-}25^\circ$). At this range, the pair of cables on both sides are slacking and the distal tip does not move until the slacking is diminished. The result of the dead zone range provided a reference to determine the actual zero position of the endoscope in the initialization of the system. In addition, the operator could have more control over the system by being conscious of the motion states of the endoscope from the hysteresis profile (Fig. 6e,f). For example, when the endoscope approaching the dead zone, it is foreseeable there will be a delay between foot command and the endoscope tip bending motion. Accordingly, the operator could make proper control decisions to move the endoscope smoothly.

3.2 Surgical task performance

The operation of the surgical task is depicted in Fig. 7. The operators viewed the robotic instruments and tissue through the endoscopic camera view (Figs. 7b,d). For the exposed targets shown in Figs. 7a,b, each operator was required to directly cut the tissue within the marked zone; for the covered target, see Figs. 7c,d, the operator should lift the tissue using their left hand controlling the grasper and cut inside with hook. Figs. 7e,f show the cutting result of one participant. The trial was regarded as failure if the operator did not cut in the target zones.

The completion times of each subject using foot and hand clutch control modes in four sets are shown in Table 4. All the participants could complete the surgical task within ten minutes with both control modes. The whole surgical system is user-friendly for new users. In addition, the time was reduced in all participants by using foot rather than hand clutch control, with $217.4\text{ s} \pm 93.3\text{ s}$ relative to $312.5\text{ s} \pm 112.5\text{ s}$ ($p = 0.003$, Mann–Whitney U test). Four of six of the participants had their operation time reduced by 40 - 50% when using foot control {44.4%, 50.3%, 46.8% , 51.6%}, one participant exhibited a lower (8.7%) and one a higher (91.3%) time reduction relative to hand clutch control.

Figure 7: Surgical operation of (a)(b)exposed and (c)(d) covered targets viewed from top camera and endoscope camera. Cutting result for (e) exposed and (f) covered targets.

3.3 Subjective assessment

The questionnaire and its results are shown in Table 2 and Fig. 8. The participants felt that less mental effort was required in foot control than with the hand clutch ($p = 0.021$, Mann–Whitney U

Table 4: Completion time of six participants

Operation mode	Set number	Completion time (second)					
		Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6
Foot & hands	1	322	492	132	194	306	129
	2	305	353	158	185	122	158
	3	320	255	145	154	156	132
	4	265	248	211	131	181	164
Hand clutch	1	530	436	300	336	397	248
	2	442	363	187	409	290	318
	3	572	424	253	285	232	172
	4	243	242	231	240	204	146

Figure 8: Results of questionnaire.

test). The rating of efficiency, comfort and easiness for foot and hand clutch control was not statistically different ($p = 0.74, 0.37, 0.16$, Mann–Whitney U test) but on average slightly higher with the foot than with the hand clutch. Five of six of the participants preferred using the foot interface working together with hands to operate the system. One participant reflected “Foot control is tiring, especially in the holding gesture to wait the endoscope to move”. However, most of the individual comments reflected the ambiguity of bimanual operation with clutch solved by the additional foot control, e.g. “Using hand clutch cannot conduct simultaneous movement of endoscope and instruments”, “There is coupling on both hands, i.e. when using one hand to control the endoscope, the

other hand holding the tool moves together unconsciously”, “It is a little bit confusing sometimes whether the hand is controlling the endoscope or the tool”.

4 Discussion

The experimental study has validated the design concept and the feasibility of the novel three-limb teleoperated endoscopic robotic system. All the participants could telemanipulate two surgical instruments and one endoscope to intuitively conduct the surgical task using hands and foot simultaneously. The average completion time per set ranged from [161.5 - 337.0] s for foot-hands three-hand control, and from [242.8 - 446.8] s for hand clutch bi-manual control, then the operation time was reduced in average by 43.7% using the proposed system. Furthermore, no discomfort or difficulty was reported by the participants, foot control enabled achieving a similar level of efficiency, comfort and ease of use compared to hand control. Most of the participants even felt the mental effort required for the operation using the foot-hands control mode as low.

The proposed system enables one operator to telemanipulate three tools using foot and hands, with the following advantages:

- The allocation of the tasks for hands and foot corresponds to the natural motion of the limbs and ergonomics. The proposed system yields a clear role for each limb avoiding confusion on which instrument is controlled, in contrast to control with hand clutch that was also tested in above experiment.
- The foot control provides unique features relative to existing systems in endoscopic surgery: (i) Foot control provides control independent from hands, avoiding potential coupling issues between left and right hands, or hands and fingers. (ii) The system uses natural foot gestures controlling the flexible endoscope in four DoFs based on isomorphic mapping. The foot interface collects continuous foot gestures, providing foot support and positioning assistance while minimizing the operation fatigue.³¹

Few robotic systems have been proposed that are based on a long flexible shaft and allow three-tools robotics teleoperation. The EOR, FLEX, RAFE systems^{7,17,18} have a robotic endo-

scope but with manually controlled instruments. The MASTER system^{10,41} developed by our group provides dexterous tele-manipulation of two instruments based on a dual-channel gastroscope with articulated arms at the distal tip, where the endoscope has to be manually controlled at the patient side by a second endoscopist. The K-Flex system¹⁶ has an endoscope with enhanced payload capability allowing totally 14 DoFs movements of the three slave instruments. The bi-manual master interfaces could only control two surgical tools simultaneously, while the third tool is controlled by the left hand after pressing a foot clutch. In our system the 13 DoFs can all be activated simultaneously to perform a surgical operation. To our knowledge, this is the first teleoperated robotic system for endoscopic surgery with foot control offering the possibility to tele-manipulate the three flexible surgical instruments together.

While the experimental results reported in this paper are promising, important limitations need to be mentioned. First, the current foot interface can control four DoFs, which may not be sufficient to control some surgical tools, such as Endowrist Instruments of the Da Vinci system, which has up to seven DoFs. Secondly, the current slave robotic system is bulky, and a more compact version would be needed in an actual operation room (OR). This new version will also include water/gas and suction control buttons in the master console, which could be commanded using the second foot.^{42,43} Furthermore, one participant reported fatigue while using the foot control, perhaps due to the large force he exerted when the endoscope was in the dead zone. This inherent motion backlash of the non-linear tendon-driven mechanism may be improved using machine learning techniques and adaptive control.^{44–46} At the current stage, the surgical operation study was conducted with subjects without medical background, which was designed to validate the feasibility of the proposed robotic system. In the future, systematic studies for more complex surgical procedures like ESD will be carried out with professionals, to further test its practicality in real-life surgery.

5 Conclusion

This paper has presented a complete three-limb teleoperated robotic system for flexible surgical instruments and standard endoscope. The system has in total 13 DoFs, consisting of a robotic endoscope and two hand-controlled robotic arms, which can be intuitively teleoperated using two

hand interfaces and a foot-controlled interface. The proposed system allows a single operator to simultaneously tele-manipulate both the endoscope and instruments without an assistant. In an initial experiment with naive subjects, three-hand control with the foot using this system was shown to be more efficient than two-hand clutch control and to require less mental effort. Participants without experience of handling the endoscope and robotic instruments found that the proposed system with the foot control is easy and intuitive to control in a pseudo-surgical task. Three-limb teleoperated surgery can arguably improve the efficiency and save manpower. However, comprehensive preclinical studies and in-vivo tests with surgeons are needed to further validate the concept in real-life surgery.

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