
Performance evaluation of a foot interface to operate a robot arm

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Abstract: We developed a foot interface enabling an operator to control a robotic arm with four degrees of freedom in continuous direction and speed, for operating one of the multiple tools required during robot-aided surgery. In this paper, we first test whether this pedal interface can be used to carry out complex manipulation as is required in surgery. Second, we compare the performance of ten naive operators using this new interface and a traditional button interface providing axis-by-axis constant-speed control. Testing is carried out on geometrically complex path-following tasks similar to laparoscopic training. Movement precision, time and smoothness are analyzed. The results demonstrate that the continuous pedal interface can be used to control a robot in complex motion tasks. The subjects kept the average error rate at a low level of around 2.6% with both interfaces, but the pedal interface resulted in about 30% faster operation and 60% smoother movement, which indicates improved efficiency and user experience as compared with the button interface. A questionnaire shows that controlling the robot with the pedal interface was more intuitive, comfortable, and less tiring than with the button interface.

Key words: Telerobotics and teleoperation, dexterous manipulation, performance evaluation and benchmarking.

0 INTRODUCTION

Robotic surgery often involves three or four robotic arms (two for interventions and one for the camera) [1]–[3]. Controlling all the arms simultaneously without any additional assistants may enable the surgeon to improve the operation's efficiency and safety, as this would avoid communication errors between the surgeon and assistants. Therefore, interfaces using speech or the movement of the head, foot or finger have been introduced to re-position the laparoscopic camera from time to time [4]–[6]. Arguably, interfaces with continuous control may provide more benefits. In this context, the studies [7], [8] have demonstrated how a virtual “third arm” can be controlled by foot continuously and simultaneously with the hands to carry out a common task.

While teleoperating a surgical robotic arm with the hand has been extensively studied, e.g. [9], [10], it is still unclear how the foot should be used to effectively and intuitively control a multiple degrees of freedom (DoF) robotic arm. Perhaps because the feet are less dexterous than the hands [11], most existing foot interfaces in surgical applications consist of simple switches or buttons that operate one function or movement in one DoF, such as to activate the bipolar forceps [12], or to interact with the image in radiology interventions [13].

Current foot interfaces used e.g. to control a laparoscopic camera [14]–[16] consist of multi-directional switches placed on a planar platform, where each switch moves the robot in one direction with constant speed. Such interfaces are relatively easy to use for simple tasks where the binary foot input can capture the task. However, the operation may become more difficult and less efficient to control for multiple DoFs' movements of the robot when frequent or continuous direction adjustments are required. Furthermore, the number of buttons will grow with the number of directions to be controlled, increasing the complexity of operation and the risk of mistakes. These interfaces also demand the operator to plan the movement in discrete single Cartesian directions, identify correct buttons without looking at the foot, and then carry out a suitable pressing sequence and time. These operations may cause fatigue with float-in-air foot gestures and mental effort to select a correct buttons sequence.

Therefore, we have developed an alternative pedal interface that can be used to continuously control a robot's movement in direction and speed magnitude, and may address the issues with

interfaces made of simple switches mentioned above. This four-DoF interface also provides force feedback, offers a resting posture [17], and uses natural foot movement patterns and forces. The objective of this paper is to explore the operation enabled by the novel pedal interface in a four-DoF task characteristic of the targeted surgical application.

The interaction should yield an intuitive and natural mapping, require small foot movements but provide a large control range for the output commands, with accuracy and little effort during long operation times.

The paper reports the study we have carried out with ten naive subjects to test the operation with the novel foot interface, and compares the developed interface with a conventional interface using multiple foot switches. Ten participants used these two interfaces to operate a robot and carry out the task with the dominant foot. A path following task which requires accuracy and dexterity in four DoFs (three translations and one rotation) was used. The performance was analyzed in term of the operation error rate, task completion time, motion smoothness, as well as through a subjective questionnaire. The rest of paper is organized as follows. Section 1 introduces the two foot interfaces with their mapping and control methods. Section 2 then describes the robot control system and the experiment protocol. Section 3 presents and interprets the experimental results, and Section 4 gives brief conclusions.

1 FOOT INTERFACES

1.1 Pedal interface

1) Interface design: The four-DoF motion of a laparoscopic tool (Fig.1a) can be intuitively mapped to the foot motion (Fig.1b). The foot lateral/medial rotation (shank roll) corresponds to the roll of the tool, the flexion/extension of the knee joint (shank pitch) to the pitch of the tool, and the abduction/adduction of the hip joint (shank yaw) to yaw rotation of the tool. Furthermore, we select the foot dorsiflexion and planarflexion (foot pitch) for the in/out translation of the laparoscopic tool. This is because using foot lifting up and down would need to move the whole leg and support it against gravity, which would be tiring during long operation.

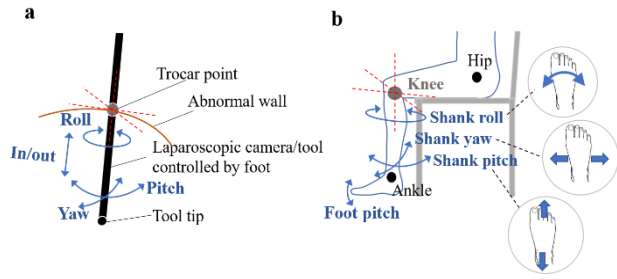


Fig. 1. Using natural movement patterns to command a laparoscopic instrument such as a camera. (a) Four-DoF movements of the laparoscopic instrument. (b) Mapping and the foot gestures used to control the four-DoF.

The pedal interface (of dimension 56.8x37.2x10.2cm³) shown in Fig.2a was designed based on the aforementioned foot movements. The mobile coordinate of the pedal plate can be represented as x_f, y_f, z_f . The movements in translations of x_f ; y_f and rotations around y_f and z_f , represented as θ_f and ϕ_f , and any possible combinations of them can be by the foot and collected by the interface.

The pedal interface has a hybrid parallel-serial structure consisting of a base, a mobile frame (MF), a pedal plate with adjustable foot fixture and eight serial elastic sensing modules (SES). The pedal plate supports the leg against gravity in order to minimise effort. Eight universal wheel bearings mount on the bottom of the MF to reduce the dragging friction to facilitate the horizontal foot motion. The foot fixture, which can be adjusted to different foot sizes, is used to transmit the applied force. A detailed description of the design is contained in [17].

The eight SES are located around the foot (Fig.2a) to capture four-DoF force and position of the foot (within a small workspace: ± 2 cm translation, $\pm 12^\circ$ rotation). Meanwhile the base and the MF (including the pedal) form the parallel structure with six horizontally arranged SES incorporating a compression spring. The pedal is serially connected with the MF through a pivot shaft and two SES with torsion springs. Each SES is composed of an elastic element connected to a load cell, which senses the applied force from the deformed elastic element (and thus position displacement). Once the elastic element reaches the motion limit, isometric force can further build up and be recorded.

2) Identification of subject-specific interaction patterns: Habitual foot movements in desired directions may not correspond exactly to the interface axes. Specifically, we have found that the desired movement direction patterns vary little between consecutive trials of any specific subject, but are different between subjects. Therefore a data-driven calibration procedure was developed to identify subject specific motion patterns [17].

In this calibration the subject is asked to conduct foot motions using the interface in eight directions: forward (F), backward (B), left (L), right (R), toe up rotation (TU), toe down rotation (TD), left torsion (LT), and right torsion (RT) as shown in Fig.3. Starting at the home position, the subject moves the pedal smoothly in each specified direction to the boundary of the workspace, holds it for one second at a comfortable force level, and releases it so that the foot returns back to the home position. Three movements are conducted in each direction. The procedure is carried out until all the 3x8=24 centre-out and back movements are completed. From this data, a mapping

$$\mathbf{D} = \mathbf{Tf}$$

is formed to compute the control command $\mathbf{D} = [x_f, y_f, \phi_f, \theta_f]^T$ from the force sensors signals $\mathbf{f} = [f_1 \dots f_8]^T$. The 4x8 transformation matrix \mathbf{T} is computed using independent component analysis (ICA), which defines the motion axes based

on the individual operator's motion characteristics [17]. These control commands are mapped to the robot velocity \mathbf{v}_t , from which the robot's position \mathbf{P}_t can be integrated:

$$\mathbf{P}_t = \int_{t_1}^{t_2} \mathbf{v}_t dt = \begin{bmatrix} x_t \\ y_t \\ \phi_t \\ z_t \end{bmatrix}, \quad \mathbf{v}_t = \mathbf{sD}$$

Where \mathbf{s} is a diagonal weighting matrix.

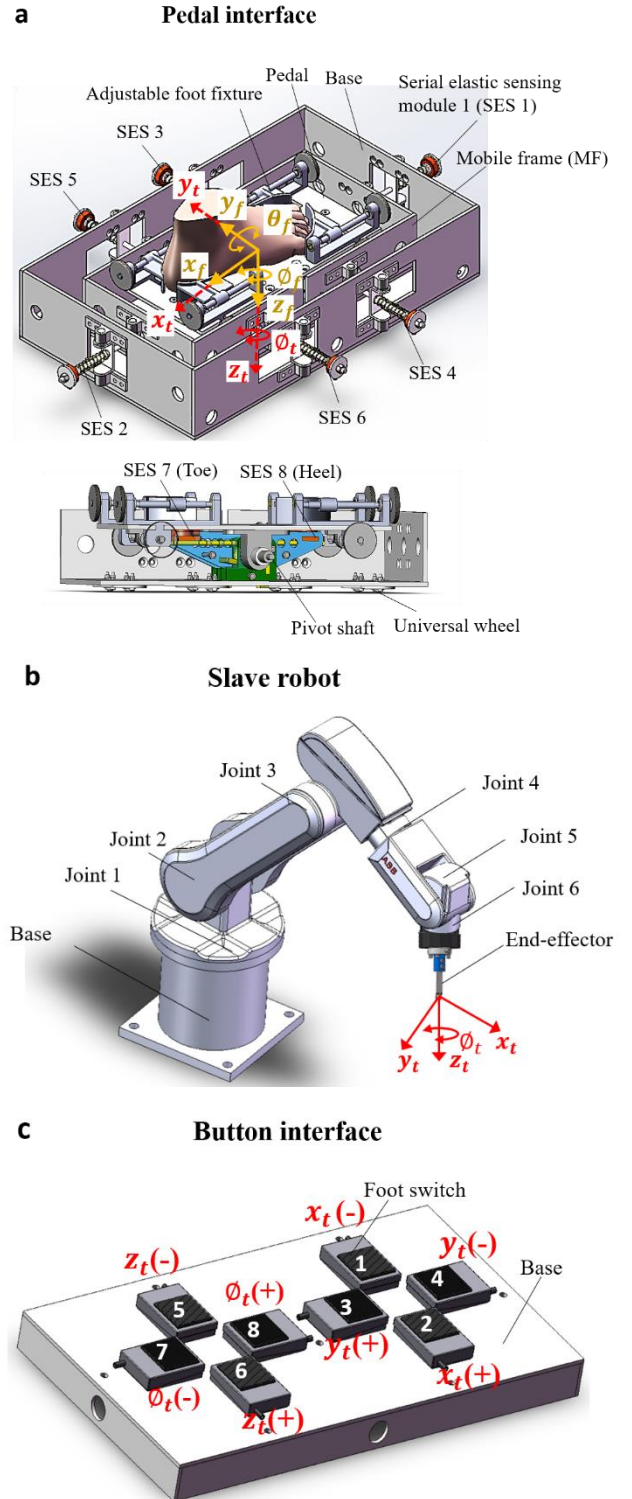


Fig. 2. Different interfaces to control the robot. (a) Pedal interface in perspective top and open side views. (b) Slave robot. (c) Button interface coding robot movement directions.

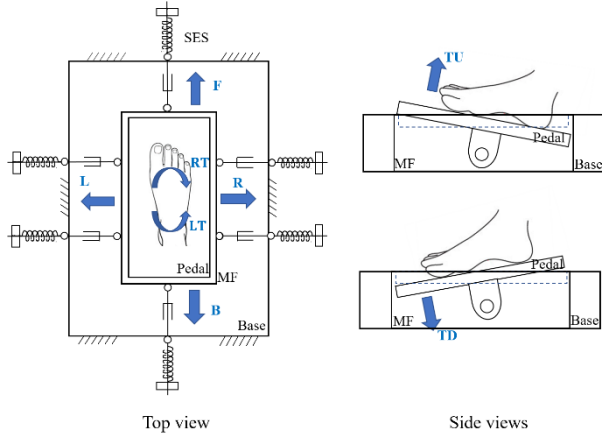


Fig. 3. Motions in eight single directions (F: forward, B: backward, L: left, R: right, TU: toe up rotation, TD: toe down rotation, LT: left torsion, RT: right torsion).

3) Mapping to robot coordinates: The mobile coordinates of the foot interface in x_f, y_f, θ_f (Fig.2a) are mapped to the coordinates x_t, y_t, θ_t of the robot end-effector (Fig.2b) respectively. The rotation DoF θ_f of the foot interface maps to the vertical translation z_t of the robot with anti-clockwise rotation in θ_f corresponds to positive z_t and clockwise rotation controls negative z_t . The slave robot speed is controlled without workspace limitation, where the robot velocity is proportional to the force exerted by the foot. A dead zone is used for each DoF control command to prevent the robot from moving with small involuntary foot movement. The maximum speed is limited to a target value based on different applications.

1.2 Button interface

1) Interface design: The button interface (of dimension $65.2 \times 35.6 \times 5 \text{ cm}^3$) shown in Fig.2c was designed similar to existing commercial foot interfaces [14]–[16], with four DoF controlled using eight $9 \times 6.6 \times 2.4 \text{ cm}^3$ foot switches with $5.5 \times 5.5 \text{ cm}^2$ pressing area. These eight foot switches are placed on a planar base. Pressing one foot switch activates a constant speed movement in the related Cartesian direction. A skilled operator may use two buttons simultaneously with one foot to combine movement in two directions. The button interface is advantageous to control motion in single directions without direction deviation. However, more complicated tasks requiring movement combining multiple directions and frequent redirection will require planning, which may lead to long operation time, fatigue and yield jerky trajectory.

2) Mapping to robot coordinates: The foot switches are arranged to match the spatial azimuth relationship of the robot motion (Fig.2b,c). The left four switches control the translation and rotation of the robot's z_t axis. Buttons 5 and 6 control negative and positive z_t , respectively; buttons 7 and 8 map to the clockwise and anti-clockwise rotation around the z_t axis. The right four switches correspondingly control the robot in horizontal translations, i.e., buttons 1 and 2 activate the movements of the robot in x_t negative and positive directions; buttons 3 and 4 control positive and negative directions along y_t . The on/off state of each of the eight buttons is sent to the master computer and each pressing will command the robot to move at constant speed in the corresponding direction.

2 EXPERIMENT

2.1 Experimental conditions

An experimental study was conducted to evaluate the feasibility of using the pedal interface for controlling a robot in four DoFs in a pseudo surgical task, and to compare the performance with a conventional foot interface based on discrete switches. The experiment was approved by the Institutional Review Board of Nanyang Technological University (IRB-2018-05-051). Ten participants (five males and five females) with an average age of 28.7 ± 2.2 years, without motor impairment, were recruited for the experiment. Their foot sizes ranged from 37 to 43 (40.1 ± 2.4) in the European standard. These participants were all right-footed according to the ball-kick dominant leg test [18], and none of them regularly used any foot based control systems. They were informed about the experiment's purpose and protocol, and signed a consent form before starting it.

The teleoperation system used in our skillful operation experiment (shown in Fig.4) includes a master interface and a slave robot arm. This robot is a six-DoF manipulator (IRB120, ABB Robotics) with serial structure described in Fig.2b. It is controlled using external guided motion (EGM) mode [19], which enables a 30Hz response to commands from the foot interface. A low-pass filter with 10Hz cut-off frequency was used between the sensor signals and the robot motion controller. The maximum and constant speeds for the robot end-effector was set to 0.6 cm/s in translation and $10^\circ/\text{s}$ in rotation when controlling with the pedal interface and button interface respectively. These limits were set in preliminary trials carried out by the experimenter with the aim to offer comfortable control.

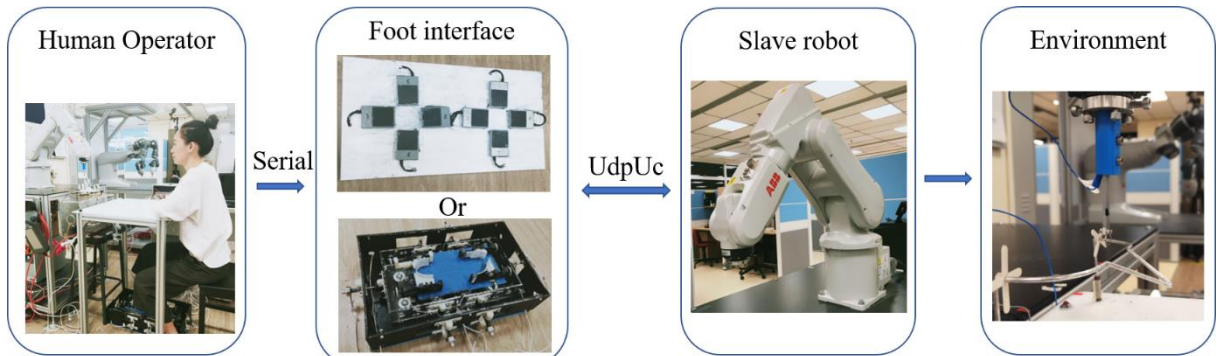


Fig. 4. Teleoperation system control network.

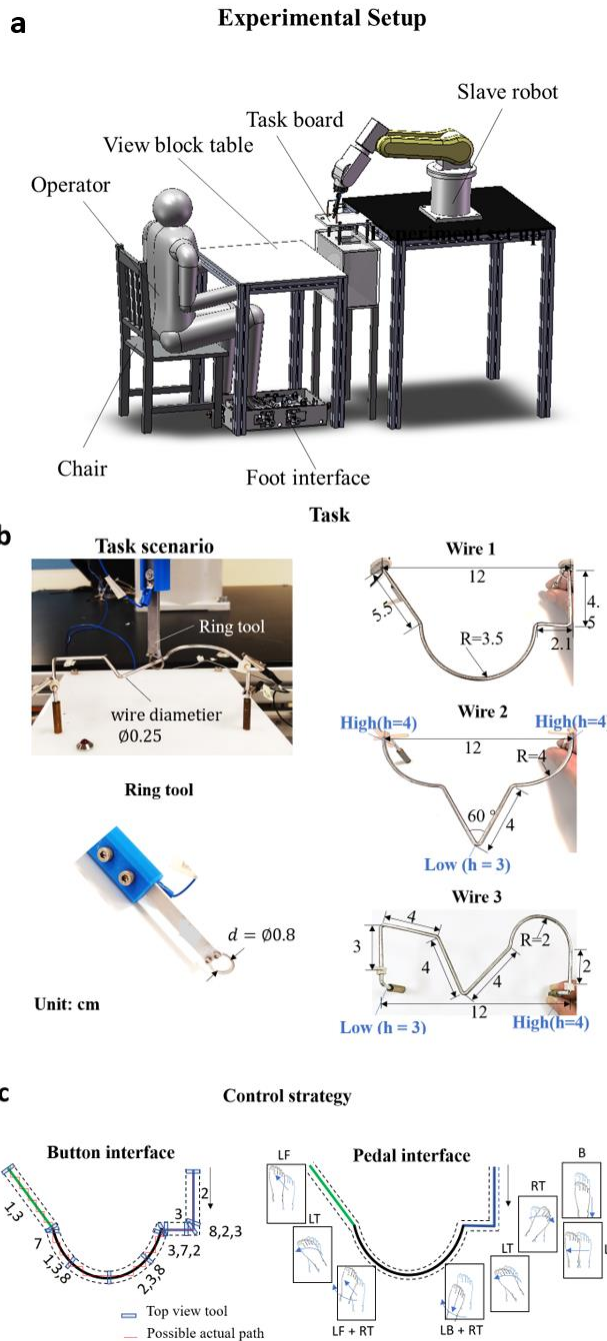


Fig. 5. Experiment overview. (a) Experimental setup. (b) Task scenario (left top), enlarged views of robot end-effector tool (left bottom) and three training and testing wires (right). (c) Possible control strategy for the button interface (The numbers on the left panel represent the buttons used during movement) and the pedal interface (B: backward, L:left, RT: right rotation, LT: left rotation, LB: left and backward, LF: left and forward).

The human operator moves the foot in the pedal or button foot interface, the continuous or discrete foot information is then transmitted to the computer through serial communication. The interface's output is mapped to four-DoF robot velocity control commands through mapping models of foot interfaces. The corresponding robot configuration is then sent to the robot controller through the User Datagram Protocol Unicast Communication (UdpUc), in which the computer acts as the server and the robot controller is the client.

Either foot interface was placed on the ground in front of the subject, who was comfortably sitting on a fixed chair and controlling the end-effector (with the dominant foot) using direct visual feedback of the end-effector (Fig.5a). A 66x58x80cm³ large block view table was placed between the foot interface and the participant to prevent the operator from watching the foot or the interface during operation.

2.2 Protocol

1) Calibration and habituation: Five minutes were given to the participant to get familiar with the system operation before starting the test trial with each interface. The calibration procedure was conducted as described in Section 1.1. The mapping model for interacting with the pedal interface was first given to the participant for two minutes during which they could test the mapping model to control the robot movements. The same time was given for the participants to familiarize with the use of the button interface.

2) Task: The task is as in the laparoscopic training system of [20], but conducted with an industrial robot and using foot control. The participant is asked to move the robot end-effector along each of three wires as fast and accurately as possible without hitting the wire. The test scenario, robot end-effector tool and testing wires are shown in Fig.5b. A small ring with 0.8cm inner diameter fixed to the robot's end-effector is guided along a 0.25cm diameter aluminum. Three wires with different shapes define various path characteristics including: 1) single Cartesian path along x_t, y_t , 2) two-DoF diagonal path in x_t-y_t plane, 3) two-DoF translation and one-DoF rotation circle path, 4) the above paths and combined translation in z_t and 5) turning points with angles of equal, less or larger than 90°. Wire 1 is a 2D horizontal path. Wires 2 and 3 are 3D routes with height difference in z_t axis of 1cm. Experiments with the first two paths is considered as training and conducted on a first day while the third path is used on a second day to test the acquired skill. Half of the participants start (on both days) using the pedal interface and then the button interface while the other subjects start with the button interface.

The starting position of the ring tool is at one side of the wire. One trial is completed when the tool is moved from one side of the path to the other side. The odd-numbered trials start from left to right, and the others start from right to left. There is a 10-second short break between consecutive trials. After finishing 10 trials at wire 1 with one interface, the subject relaxes for a 2 minutes break, after which wire 2 is used. After finishing practicing with these two wires with one interface, and a 5 minutes break, the same protocol is followed with the other foot interface. Test on wire 3 is carried out similarly on the second day.

2.3 Performance measures

relatively strict accuracy constraint is selected for footcontrol of within ± 0.275 cm in x_t, y_t and z_t , which is similar to the typical accuracy of 0.1 to 0.5cm in hand teleoperation system [21]. The expected control strategy for both interfaces are shown in Fig.5c with path 1 in top view as an example. The dashed lines show the maximum allowable deviation when the ring tool's cross-section is perpendicular to the path and concentric with the wire circle cross-section. The participants' performance with foot control is assessed through the error rate, completion time, smoothness and the subjective questionnaire.

Table 1 SUBJECTIVE ASSESSMENT QUESTIONNAIRE

No.	Statement	Score
1	The mapping between foot and robot movement is not intuitive	1 2 3 4 5 very intuitive
2	Accurately following the path was difficult	1 2 3 4 5 easy
3	The mental effort required for operation was low	1 2 3 4 5 high
4	Foot fatigue was	1 2 3 4 5 very high
5	Operation speed was	1 2 3 4 5 too fast
6	General comfort was	1 2 3 4 5 very comfortable
7	Overall the input device was	1 2 3 4 5 easy to use
8	Movement during the operation was	smooth
9	In general, which interface do you prefer? Why? Please specify your reason(s)	

a) Completion time: The completion time is the most direct measure index of performance in teleoperation control. The time is recorded from when the robot starts to move (i.e. when quitting the start metal plate) until the ring tool touches the end metal block. The task is carried out back and forth, where one trial corresponds to either the forth or back movement.

b) Tracking error rate: The operator needs to dynamically adjust the ring via foot control while avoiding touching the wire. When the wire is touched, the buzzer is on which is recorded at 20Hz. The error rate in a trial is the percentage of touching time divided by the completion time.

c) Smoothness: Motion smoothness at the slave robot can be used to reflect the foot motion control performance. How smooth or jerky the movements of the slave robot is quantified using the absolute value of the spectral arc length smoothness metric [22].

d) Questionnaire: At the end of the task, participants were given a questionnaire of Table I, containing nine questions to assess the use of the two interfaces to control the robot. The first eight statements are rated on a discrete fivepoint Likert scale.

3 RESULTS

3.1 Behavioural analysis

We see in Fig.6a that using the pedal interface, the subjects could achieve a relatively high robot motion accuracy, characterized by a low error rate of 1-4%, with both the button and pedal interfaces (t-test, $p > 0.13$). Furthermore, the pedal interface enabled the subjects to reduce the time (Fig.6b) to complete the task (t-test, $p < 0.006$) by about 30% with all three wires relative to when using the button interface.

The average jerkiness at the slave robot in translation (Fig.6c, top row) and rotation (Fig.6c, bottom row) were analyzed separately. The spectral smoothness index of translation increased (t-test, $p < 0.014$) by 63%, 59% and 56% using the pedal interface allowing continuous direction changes relative to the button interface for the three tracking paths. The robot's rotation movements also became smoother (t-test, $p < 0.045$), with exception of the second path (t-test, $p = 0.060$), by 48%, 22%, 30% along the three wires, respectively, when using the pedal interface rather than the button interface.

Learning can be observed through the completion time and jerkiness. The completion time in the first wire reduced by about 28% in the last three trials compared to the initial three trials when using either the button or the pedal interface. The learning rate slowed down on the second path, probably due to the learning experience along the first path. Movement in the third wire was conducted on the second day, where the results suggest some re-learning. The pedal interface yielded a faster learning rate with 24% reduction on the completion time from the first three to the last three trials, and 9% with the button interface. The jerkiness on translation exhibited a similar learning effect as the

completion time.

The results did not depend on the order in which the interfaces were used (t-test, $\min(p) > 0.07$) or the order of robot movement directions (left to right vs. right to left, t-test, $\min(p) > 0.17$) for all the metrics. Therefore, all data could be analyzed together. Fig.6 compares the average performance metrics over the first and last three trials when using both interfaces.

3.2 Foot control in complex motion

To further examine the foot motion control capability, we analyzed performance along wire 1 separated in three parts: straight, then circle and then diagonal segments, as indicated through different colors in Fig.5c. Compared to the button interface, the pedal interface let the subjects save on 23.5%, 42.5% and 30.9% less time on the three sub-paths, respectively. The pedal interface led to improved performance especially on the circle path that requires three-DoF control. As the number of samples in a trial is mainly affected by the time taken to complete the task, the dynamic time warping technique was used to determine the optimal alignment between the reference trajectory and the trajectories with the two interfaces. The path deviation calculated as the sum of the Euclidean distances between corresponding points was then computed after alignment. Although the time and accuracy are in tradeoff, the pedal interface enabled the operators to both shorten the time and increase accuracy when completing the circle path, with 34.5% less deviation than when using the button interface.

3.3. Subjective Assessment

Fig. 7 illustrates the average responses (and the standard deviation) of ten participants to the questionnaires of Table I, developed to assess the robot control with the two interfaces. An Analysis of variance (ANOVA) was conducted on the 10 subject's responses of the two foot interfaces, using a 5% significance level.

This test revealed that the choice of interface had a significant effect on the rating of intuitiveness ($F(0.05,1,18) = 40.02$, $p < 10^{-5}$). Participants found that the mapping is more intuitive using continuous foot movements in all directions (with a mean responses of 4.4 for the pedal interface and 2.7 for the button interface). The ANOVA also revealed that the foot control strategies had a significant effect on physical fatigue ($F(0.05,1,18) = 14.4$, $p = 0.0013$). The button interface (4.30 ± 0.82) was felt to require larger physical effort than the pedal interface (3.10 ± 0.56). Significant effects were also found for the criteria of comfort ($F(0.05,1,18) = 13.46$, $p = 0.0018$), ease of use ($F(0.05,1,18) = 8.23$, $p = 0.0102$), and smoothness ($F(0.05,1,18) = 7.36$, $p = 0.0142$), where participants generally found the pedal interface was superior in those aspects.

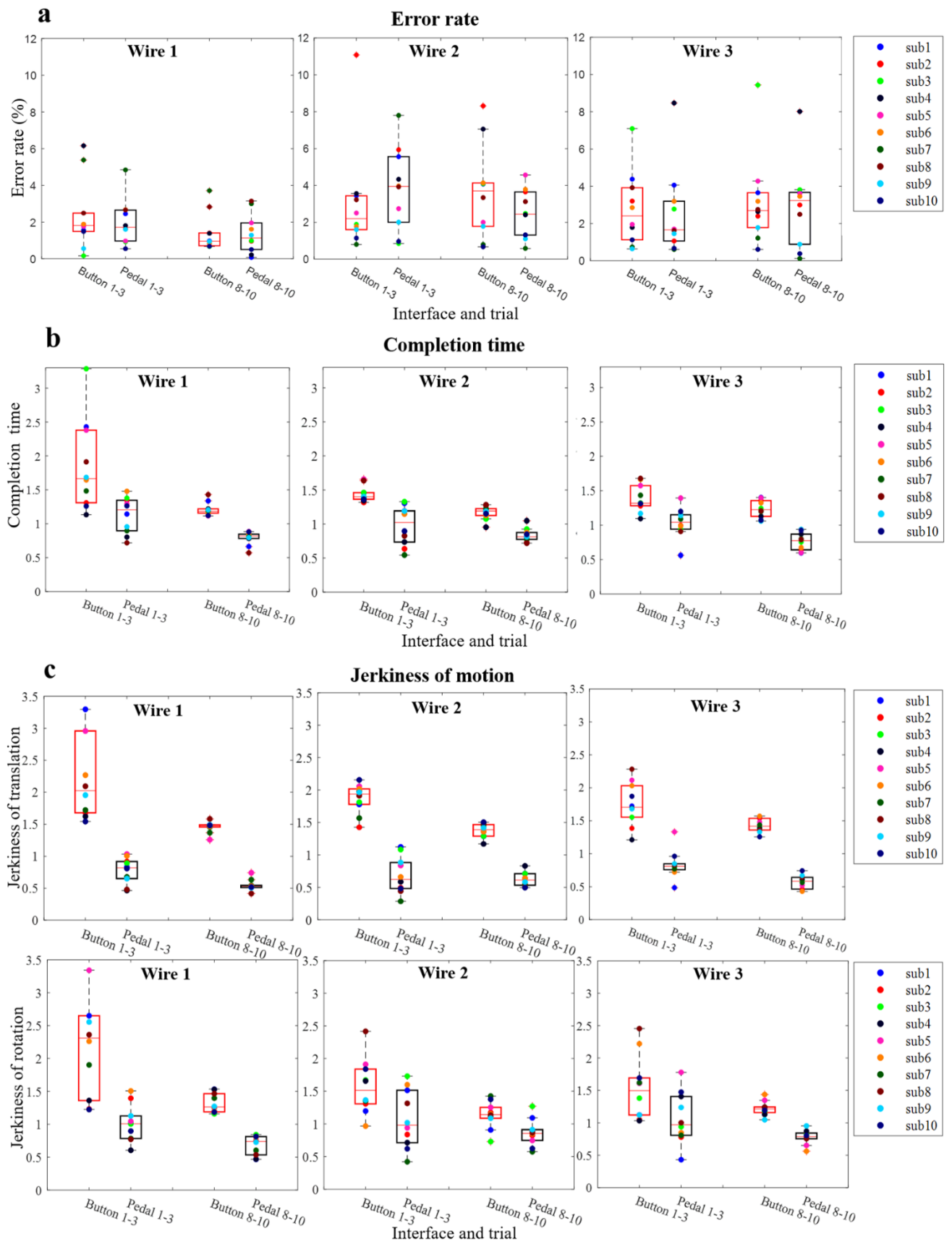


Fig. 6. Analysis of performance in the tracking task along the three wires. Error rate (a), completion time (b) and motion jerkiness (c) in the first and last three trials when using the button and pedal interfaces

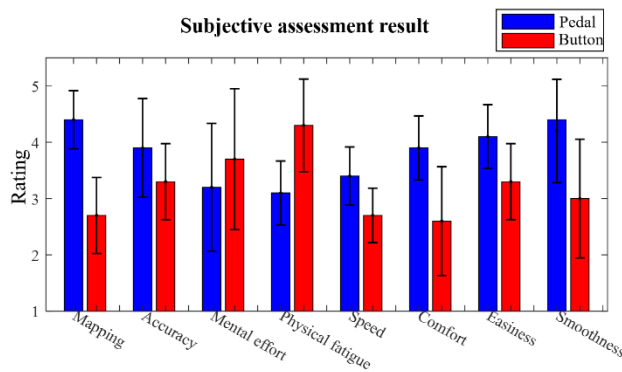


Fig. 7. Results on the subjective assessment of using the pedal and the button foot interfaces.

It is interesting to note that participants felt the robot moved at faster speed (ANOVA: $F(0.05,1,18) = 9.8$, $p = 0.0058$) using the pedal interface, although the speed was smaller or equal to the constant speed used with the button interface. No significant effect was found on the accuracy ($F(0.05,1,18) = 2.95$, $p = 0.1033$), which corresponded to the objective error rate results. Also mental fatigue ($F(0.05,1,18) = 0.88$, $p = 0.3618$) was not deemed larger with the button interface. Overall, 9/10 of the participants clearly preferred the pedal interface due to the more efficient operation and reduced fatigue.

4 DISCUSSION

This paper compared different foot control strategies to operate a robot, using a new foot pedal interface and a traditional foot button interface. Ten subjects were recruited to control the robot's end-effector in following a wire with a ring,

in a task similar to robot-aided surgery training. The subjects' behavior was analyzed using objective metrics of error, completion time and motion smoothness, as well as through a subjective assessment of a questionnaire.

The average error rate (Fig.6a) was small, generally 1-4% with both foot interfaces. This indicates that the novel pedal interface can be used to achieve the same accuracy level as with the state-of-art button interface. The 30% decrease of completion time (Fig.6b) and the 60% motion smoothness increase (Fig.6c) exhibit the superior performance enabled by using the pedal interface instead of the button interface.

These performance differences may stem from the different motion control strategies offered by the two interfaces. With the button interface, movements in different DoFs are separately controlled by the associated buttons, which results in discrete movements, time-consuming motion adjustment, and less smooth trajectories. In addition, the operator needs to plan the movement sequence, carry out many futile movements from one button to another, lift/drop the foot to release/press the buttons for multi-DoF motion control, which all prolong the motion adjustment and significantly increase physical fatigue. In contrast, with the four-DoF foot pedal interface, the natural continuous movement of the foot in multi-DoF is directly mapped to the motion of the robotic arm, leading to more intuitive and efficient operation and smoother trajectories.

The advantages of the pedal interface become particularly clear in complicated movements which require multiple DoF, such as following a circular path accurately. We have found that the pedal interface can achieve both 42.5% shorter time and 34.5% higher control accuracy on the circle path. The operator tends to change the movement direction continuously rather than separating it to single direction movements.

The results of the questionnaire show how users perceive these advantages and the characteristics of the pedal interface. The

subjects found the pedal interface superior to the button interface in terms of mapping, comfort and smoothness, which corresponds to the decrease of completion time and increase of smoothness. Interestingly, both objective and subjective measures of accuracy indicated no difference between the two interfaces. The button interface enables high accuracy (zero error if not pressing a wrong button) in controlling single direction motion but leads to deviation in multi-DoF movements. In contrast, the pedal interface has more deviation in the single directions but enables higher accuracy than the button interface in complicated tasks. Subject mental effort was also not different between the two interfaces. This may be explained as the pedal interface requires continuous movement direction control, while the button interface requires the subject to pay extensive attention on the motion-button mapping and for motion planning. The perceived lower fatigue with the pedal interface can be explained as it supports the foot and provides a resting place, while using the button interface required to lift the foot between the button during the whole operation.

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