2023 IEEE International Conference on Robotics and Automation (ICRA 2023)
May 29 - June 2, 2023. London, UK

Foot gestures to control the grasping of a surgical robot

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Abstract— **Many surgical tasks require three or more tools working together, where a hands-free interface could extend a surgeon's actions to control a third surgical tool. However, most current interfaces do not allow skilled control of grasping critical to robotic manipulation. Here we first present a systematic study to identify efficient and intuitive interaction strategies to control grasping of a surgical tool. A series of experiments were conducted to evaluate six foot pressure-based gestures. Based on the results, three modular novel foot-machine interfaces were developed, which can be integrated with other motion control interfaces. The identified interaction strategies were implemented to control a laparoscopic tool in a surgical simulator, and evaluated in a user study. The results illustrate how naive participants can operate grasping yielding smooth and pick & place operation.**

I. INTRODUCTION

Skillful control of a surgical robot by a surgeon requires an intuitive and reliable interface [1]. In teleoperated use of surgical robots, the surgeon can sit at the master console to control two tools with the hands, thereby freeing their feet to control a third tool. We developed strategies to augment the surgeon's control with foot control enabling them to use three tools simultaneously [2], which could avoid communication issues with an assistant.

Recent studies showed promising results of using foot to control a surgical endoscope [3], [4] or an industrial robot [5], [6]. However intuitive control of the grasping degree-of-freedom (DoF), critical to skillful manipulation, has been little studied. Existing control schemes typically sacrifice one foot motion DoF to control the grasping [7]–[9], or couple it with the foot motion control [10], [11].

Using toe motion or pressure can offer a solution to control grasping independently of foot motion. The foot interface in [12] records bending position of toes to control the grasping DoF of a robotic supernumerary arm. The interface of [13] uses pressure sensors placed under the big toes to control a third robotic thumb. In addition to toe pressing and bending gestures used in existing interfaces, foot gestures like toe abduction [14] and curl [15] are essential to improve balance and foot flexibility during walking, running and jumping. Although these gestures may be used to control grasping, no study has yet tested how these gestures could work together with foot motion control.

In this paper, we systematically identify intuitive foot-machine interaction strategies for grasping control. Experiments are first carried out to explore the user preference, motion and grasping coupling and control capability of various interaction strategies. Grasping interfaces developed based on the results are then systematically tested on a surgical simulator.

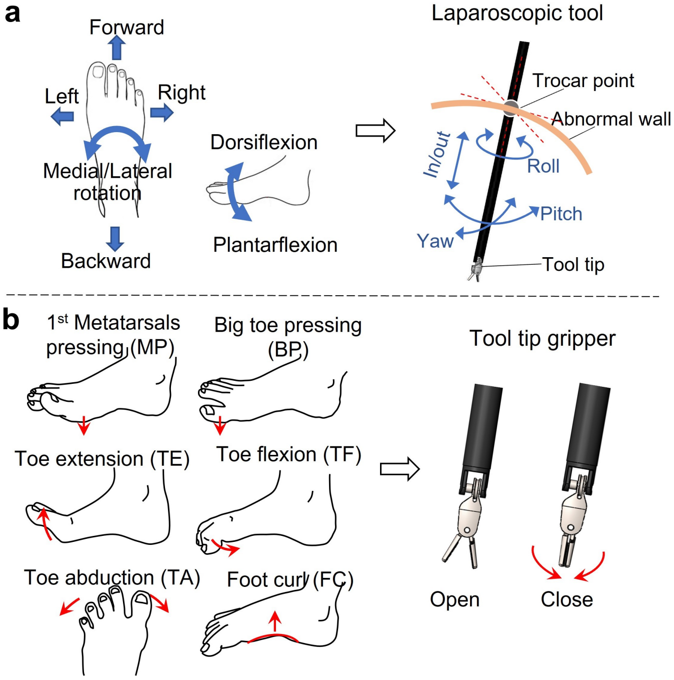

Fig. 1. (a) Foot motions (left) used in [16] to control the four-DoF movement of a laparoscopic tool (right). (b) Six potential foot gestures for controlling additionally the grasping DoF of the laparoscopic gripper.

II. GESTURE SELECTION

A. Overview

The potential foot interaction strategies for grasping control are identified based on these three considerations:

1) The operator should be able to perform the selected gestures without difficulty.
2) The selected gestures are independent of foot motion commands, i.e. the selected interactions should not affect or be affected by the foot gestures used to control the movement of the laparoscopic instrument.
3) The gesture could be able to provide continuous and accurate control on the grasping DoF.

Based on these requirements, we investigated the potential interaction strategies for grasping control in the following steps:

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*These authors contributed equally. This work was supported by the EC H2020 grants NIMA (FETOPEN 899626) and CONBOTS (ICT 871803).

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1) We first selected six potential foot gestures for grasping control (section II-B).
2) A questionnaire survey was then conducted to investigate the difficulty of performing these six gestures (Section II-C).
3) Four out of six gestures were identified based on users' responses, three modular foot interfaces were then developed to collect the remaining four gestures (section III).
4) In the next step, we conducted second experiment to assess the independent control capability of the four gestures (Section IV-A).
5) Eventually, we identified two gestures with least coupling of motion (section V-A) and evaluate them in a user study (section IV-B) with a virtual surgical simulator.

B. *Gestures library*

We have previously developed a foot interface [16], that collects four-DoF foot motions as input commands to control a laparoscopic tool (Fig. 1a): *i*) foot forward/backward movements control the pitch of the tool, *ii*) foot left/right lateral movements control the yaw of the tool, *iii*) foot lateral/medial axial rotation maps to the roll of the tool, *iv*) the dorsi/plantaflexion of the ankle controls the in/out translation of the tool.

The selected foot gestures for grasping control should not affect these foot motions commands. We built an initial gesture library with six foot gestures based on an analysis of foot biomechanics and the literature. The foot gestures, like heel pressing, are not included in the library as their obvious coupling with foot dorsiflexion and plantarflexion. The selected six foot gestures are (Fig. 1b): first metatarsals pressing (MP) [11], big toe pressing (BP) [13], toe extension (TE) [12], (TF) toe flexion, toe abduction (TA), and foot arch curl (FC).

C. *Gesture difficulty study*

A questionnaire was first used to investigate the difficulty of the six potential foot gestures. 32 subjects (with age of 21.4±2.3 years old, 16 of them male) without known motor impairment participated in the study. The demonstration figures of the gestures and the controlled surgical laparoscopic gripper were shown and explained to the participants, who were encouraged to explore the gestures as they like. Then they were requested to fill out the questionnaire by marking the difficulty of using those gestures from -5 to 5 (negative values represent high difficulty). In addition, the participants were allowed to suggest other foot gestures which they felt are more suitable to control the gripper but were not on the list. At last, they were asked to select their top three preferred gestures including the ones they suggested.

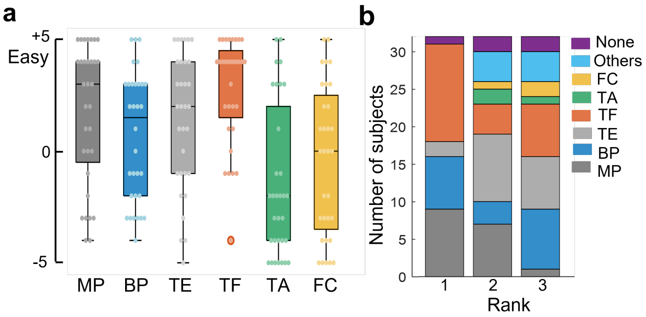

Fig. 2. Result of subjective responses on (a) the difficulty on six foot gestures and (b) the number of subjects rank top three gestures for controlling grasping DoF.

Fig. 2a illustrates the subjective responses on the difficulty of 32 participants to the questionnaire. The rating results were not normally distributed (Shapiro-Wilk test, all $p < 0.032$) and a Friedman test was run to analyze how different gestures affect the subjective rating. There was a significant difference in difficulty perception on given gestures, $\chi^2(5) = 41.869$, $p < 0.001$. Post hoc analysis showed that the participants felt gesture TA and FC are difficult with median difficulty of -2 and 0 which are below or around the neutral level. In contrast, the median difficulty for MP, BP, TE and TF were all above 1. There was a significant difference between gesture TA and gestures TE/BE/TF ($p < 0.03$) but not with BP. Gesture FC was felt more difficult than TF ($p < 0.001$) but there was no significant difference with other gestures.

The ranking for the top three gestures is illustrated in Fig. 2b. 40.6% participants preferred the TF gesture; following that, 28.1% and 21.9% participants put BE and BP as their first choice respectively; only 6.3% of them chose TE and no person choose TA or FC as their top gestures. 21.9%, 28.1%, 12.5%, 9.4% of participants chose gestures BE, TE, TF, BP as their second choice respectively, while few participants pick FC (1 of 32) or TA (2 of 32).

III. GRASPING INTERFACE DESIGN

The result of the gesture difficulty study showed that the operators found it hard to use gestures FC and TA. Thus we removed these two gestures from our list and continued to study the other four gestures. This section describes three modular interfaces that were developed to collect continuous foot pressures of MP, BP, TE and TF. These interfaces use force sensitive resistors (FSR, DF9-40, Leanstar) to collect foot pressure signals, using a 3N activation force threshold to avoid misoperation.

A. *Interface 1*

The first interface was developed to collect foot pressure of BP and MP, or any other foot planar pressure. The structure of the interface is illustrated in the left panel of the Fig. 3a. It mainly consists of a sensor tray, a pivot shaft and a locking mechanism. The sensor tray is embedded in the slot wedge of the pivot shaft. The position of the sensor tray with FSR sensor can be adjusted by translating along the slot wedge and rotating around the pivot shaft. Once the sensor is located at the proper position, it can be fixed by screwing down the locking screw (see Fig. 3a, right panel). The interface can adapt to different foot sizes through the adjusting mechanism. This interface is activated by exerting

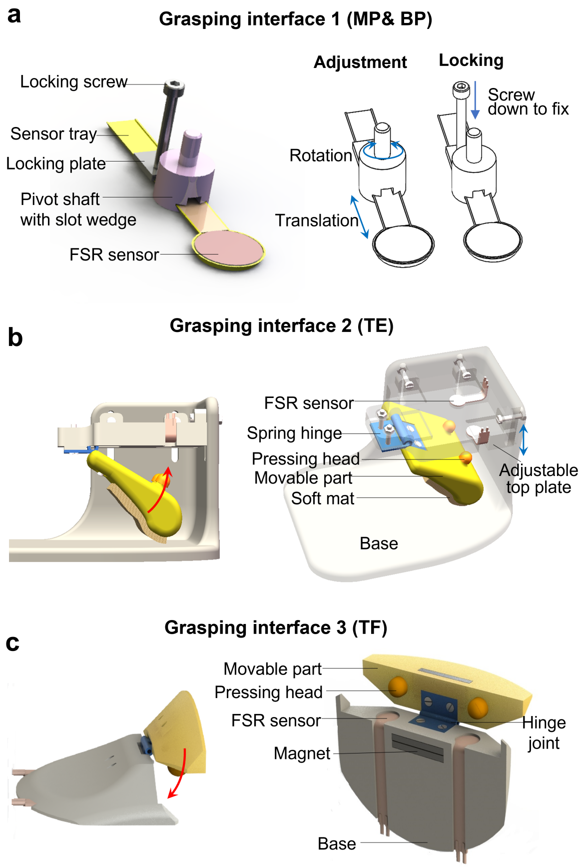

Fig. 3. Three interfaces for grasping control. (a) Interface 1 collects foot pressure under the first metatarsals or big toe; the interface can be adjusted to fix different foot sizes (right panel); (b) Interface 2 for foot gesture of toe extension. (c) Interface 3 for foot gesture of toe flexion.

force against the circular sensing area of the FSR sensor. The measured force F map to the grasper angle of the remote robot end-effector φ linearly as, $\varphi = \varphi_0 - kF$, where $\varphi_0 = 100^o$ is the initial angle, k is a scale factor.

B. Interface 2

The second interface, illustrated in Fig. 3b, was designed for the toe extension gesture (TE), mainly consisting of three parts: base, adjustable top plate, and movable part. The top plate is connected to the base, and its height can be adjusted along the vertical slot of the base wall to fit different foot sizes. The movable part is connected to the top plate with a spring hinge. When using this interface, the operator steps on the base and places their toes under the movable part with a soft mat. The execution of the toe extension rotates the movable part towards the top plate and presses the FSR sensors. Two FSR sensors are located symmetrically on the bottom of the top plate to avoid bias force from a single toe. Their average force is used as control commands with $\varphi = \varphi_0 - k\frac{F_1+F_2}{2}$, where F_1 and F_2 are the forces of the two sensors.

C. Interface 3

The third interface (Fig. 3c) was developed based on the toe flexion gesture (TF), mainly consisting of a base and a movable part. Two parts are connected with a hinge joint and separated with a repulsion force from the magnet strips on both sides. When using this interface, the operator steps on the base and locates their toes on the top of the movable part. The toe flexion rotates the movable part toward the base and exerts force against the FSR sensors on the base. Similar to interface 2, the FSR sensors are distributed symmetrically to adapt to various force-exerting approaches. The mapping between the grasping angle and foot pressure is the same as interface 2.

IV. EXPERIMENT

Two experiments were conducted to evaluate foot gestures and interfaces. The first experiment investigated the coupling effect between the proposed grasping control foot gestures and foot motions aiming to find foot gestures that are independent and not affected by foot motions. The second experiment was designed to evaluate the motion and grasping control of the proposed interaction strategies in a virtual surgical simulator. The experiments were approved by the College Research Ethics committee of Imperial College London (21IC7042). Each participant was informed about the experiments' purpose and protocol, and signed a consent form before starting them.

A. Experiment on independent control capability

Six healthy subjects (23 ± 0.63 years old, 5 males, 1 female) were recruited for this test, and all of them are right-footed. Fig. 4a-b depicts the study's experimental setup. The operator was seated comfortably on a chair, stepping their dominant foot on a pedal interface [16]. They faced the monitor which displayed virtual task feedback. The four-DoF motion of the foot in x, y, θ, ϕ are collected by the foot pedal interface. Each of the developed grasping interaction module (section III), which can collect foot pressure of TF, TE, BE and BP was integrated with the pedal interface for the respective experiments (Fig. 4b). The experiment procedure is illustrated in Fig. 4e. This test involves grasping task and motion task. The grasping task was designed to test the foot motion noise while grasping operation; Conversely, the motion task aimed to examine the foot pressure noise while performing foot motions.

1) Task 1: Grasping control: The participants were asked to control a virtual gripper to grasp an elastic ball on the screen. The four-DoF foot motion noise was recorded by the pedal interface. As shown in Fig. 4c, the gripper was in open state at the beginning of each trial with a target ball placed in the middle of it. One trial was completed successfully when the participant controlldc the gripper angle to grasp the target ball with proper force (7.3 N to 10.2 N) and held it for continuous 5 seconds. The color of the ball provides feedback on the control. The green, yellow or red colors of the ball indicate proper, too small or too large forces respectively. The trial fails when the operator does not grasp

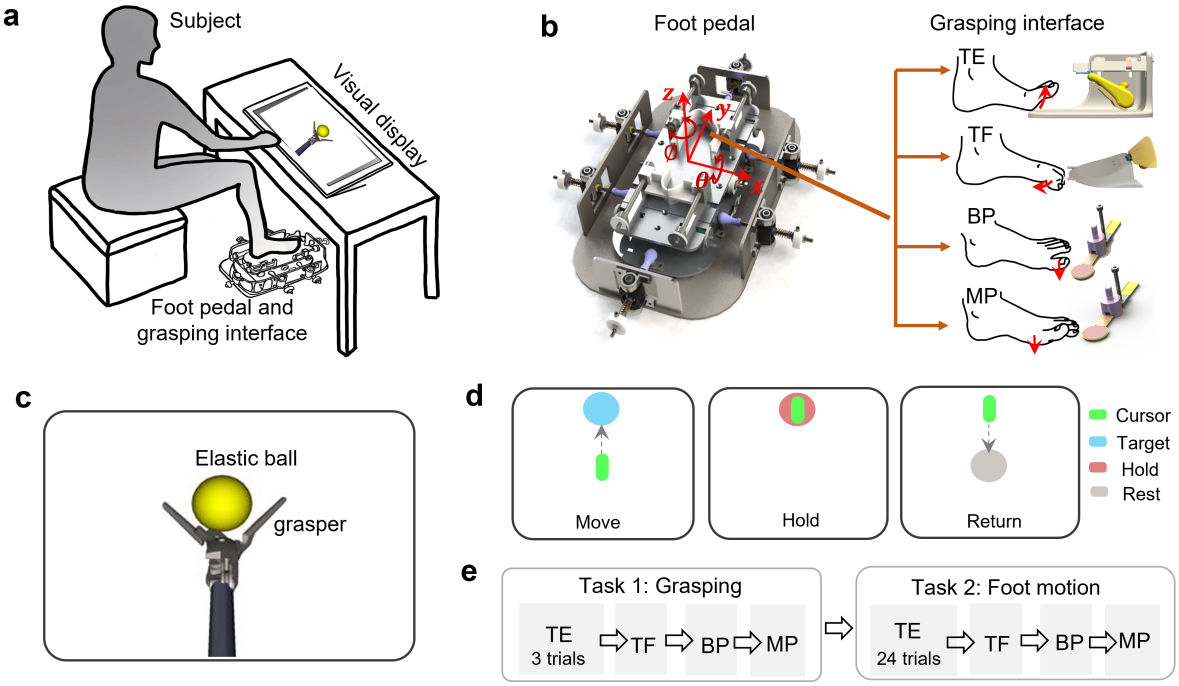

Fig. 4. Experiment of the independent control test. (a) Experimental setup with control console and operator. (b) Four interaction strategies with the foot pedal and grasping interfaces. Visual display of (c) grasping task and (d) motion task taking forward direction as an example (e) Experimental procedure.

the ball in proper force for continuous 5 seconds and the new trial will start until three successful trials have been conducted.

2) Task 2: Foot motion: The participants were asked to move the pedal from the home position along eight specified directions (Fig. 1a left). The noisy pressure (out of dead-zone 3N) during foot motion was recorded through the proposed grasping interfaces. Visual feedback was provided to the participants to guide their actions (Fig. 4d). In each trial, they were asked to follow the green motion cursor on the screen to move the pedal to the target direction to the boundary of the workspace. Once at the boundary, the pedal should be held for one second and returned back to the home position. Each session included 24 trials (8 directions × 3 repetitions). A total four sessions for four-foot gestures of TE, TF, BP and MP were conducted sequentially.

B. Experiment on evaluating grasping and motion control

The experiment setup was the same as the above experiment (Fig. 4a). Two grasping interfaces of TE and TF were tested in this experiment with a pick & place task which combines motion and grasping control. Twelve subjects (24.2 ± 3.2 years old, eight males, 4 females, all right-footed) were recruited.

1) Procedure: The foot motions and pressure were collected by the foot pedal and grasping interface, to control the motion and grasping DoFs of the end-effector of a virtual robotic laparoscopic tool in a simulator with 10 Hz teleoperation communication rate. The experimental procedure is illustrated in Fig. 5b. Half of the participants started with TE interface, and the others with the TF interface. For each grasping interface, the participants firstly attended a *training session* with a static grasping task. Then in the *test session*, each participant performed 36 trials of pick & place with 12 trials for each target size. The task difficulty was set with three different target sizes and the target ball was shown in one of four random planar positions in each trial. After the operation of each interface, the subject was required to fill in a questionnaire of NASA task load index (TLX) [17]. When they finished the experiment, they were asked to select a preferred interface and fill in the reasons for selection. The training and test tasks are also illustrated in the supplementary video.

2) Tasks: The training task is a static grasping task same as Task 1 of the above experiment but with three target sizes (large, middle and small). The successful grasping required the operator to control the grasping force in the proper range for different sizes of targets (3.6 N to 6.6 N for large ball, 7.3 N to 10.2 N for middle ball, and 10.9 N to 13.8 N for small ball). Each participant completed 3 × 3 (target sizes × repetition) = 9 trials for each grasping interface.

The test task is a picking & placing task simulating the standard laparoscopic training of peg transfer operation under the camera view. As shown in Fig. 5a, the participants are required to control the movement of the laparoscopic tool to reach the yellow ball, a grey circle will be shown to remind the operator of the proximity to the ball, then control the gripper angle to grasp the target ball, and move it to the blue target zone without dropping or squeezing the ball. At the beginning of task, the instrument was located in the bottom middle of the screen and the gripper was set in the open state. The ball will not follow the movement of the laparoscopic tool when the grasping force is too large or too small. The

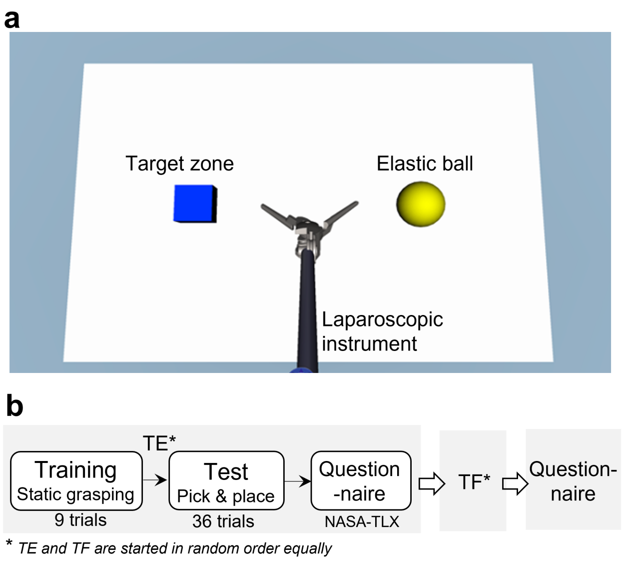

Fig. 5. Experiment of validation with a virtual laparoscopic simulator. (a) visual display of the pick & place task. (b) Experiment procedure.

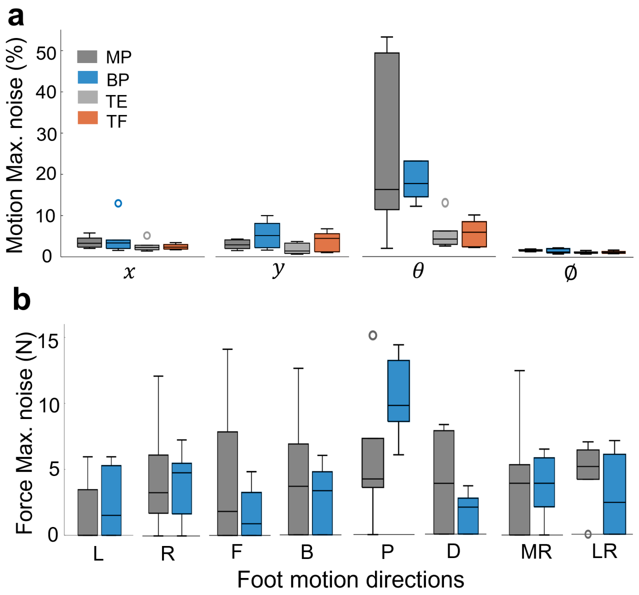

Fig. 6. Result of experiment on independent control capability. (a) Maximum motion noise of the pedal while conducting grasping operation using four grasping interaction strategies. The result is represented as the percentage of the workspace limit of the corresponding axis. x and y axes represent lateral and longitudinal translations in the horizontal plane; θ and ϕ represent pitch and yaw rotation respectively. (b) Maximum force noise of the grasping gestures while conducting four-DoF foot motion in eight directions (L: left, R: right, F: forward, B:backward, P: planarflexion, D: dorsiflexion, MR: Medial rotation, LR:Lateral rotation).

operator needs to re-grasp the elastic ball and move it again. The trial is completed until the target is transported to the target zone. Each participants performed $3 \times 4 \times 3$ (target sizes $\times$ target locations $\times$ repetition) = 36 trials for each grasping interface.

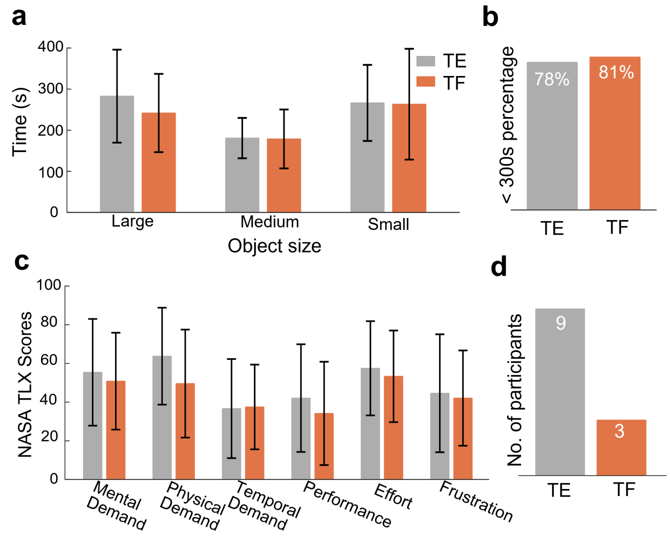

Fig. 7. Result of experiment 3 on (a) completion time (the bars depict group means, and error bars represent standard deviation). (b) percentage of participants less than 300 seconds. Subjective responses on (c) NASA-TLX questionnaire and (d) interface preference.

V. RESULTS

A. Coupling of foot motion and grasping gestures

1) How grasping control affects motion: The introduced maximum motion noise in four DoFs when the operator conducting a grasping operation is presented in Fig. 6a. The ϕ, x and y axes were less affected for all four grasping interaction strategies, the average maximum motion noise introduced was less than 6% of the pedal workspaces. However, the motion noise was obvious on θ axis which corresponds to pedal pitch rotation, especially for MP and BP interaction modes. The MP and BP grasping control affect about 24.78 ± 21.31 % and 26.46 ± 23.21% motion range of the pedal interface. While the influence was relatively small by using TE and TF grasping control modes, which only affect 5.56 ± 3.94% and 5.83 ± 3.26 of the whole motion range.

2) How motion affects grasping control: Fig. 6b shows the introduced maximum pressure noise of grasping interfaces when the operator conduct eight-direction motion. The effect on grasping modes of TE and TF are not plotted, as the pressure noise is zero for five participants and less than 1N for the remaining participant, which can be neglected. However, the foot motions, especially foot plantarflexion, affect the grasping modes of MP and BP. The maximum force under big toe and first metatarsals can reach in average 10.4 ± 3.1N and 5.8 ± 5.2N, respectively. For the foot motion in other directions, although the average noisy force is less than 6N, there is a large variation between subjects. For example, there was one subject pressed their 1^{st} metatarsals at a maximum 14.2N when moving forward while another subject had just 1.5N during the same foot motion.

B. Validation with laparoscopic instrument simulator

The performance of foot control on the pick & place task was evaluated by an objective measure of completion time and subjective responses of the questionnaire.

1) Completion time: is calculated as the total time for completing 12 trials of picking & placing for one size object (Fig. 7a). We performed a 2 × 3 repeated measure analysis of variance (rANOVA) with control mode (TE, TF) and target size (large, medium, small). There was no statistically significant interaction between the grasping mode and target size ($p = 0.37$). The main effect of the grasping mode also showed no significant difference in completion time between TE and TF ($p = 0.52$). However, the target size has an effect on the completion time ($p = 0.001$). Post hoc test with Bonferroni correction showed that the medium size ball was different to large and small size targets ($p < 0.01$). Picking & placing large or small target requires in average 262.35 ± 27.38 s or 264.89 ± 26.98 s respectively, while this time was just 179.8 ± 14.32 s for the medium size target.

We counted the percentage of participants who can complete the task within 300 seconds (Fig. 7b), which is the time limit of the peg transfer task in the standard Fundamentals of Laparoscopic Surgery (FLS) training program [18]. 78% of participants using TE control mode could complete the task within 300 seconds, and more than 80% using the TF mode.

2) Subjective responses: The NASA questionnaire result is illustrated in Fig. 7. The mental effort scores are 55.42 ± 27.59 for TE and 50.83 ± 25.03 for TF (TE vs. TF, $p = 0.49$). The perceived physical effort is slightly higher for TE (63.88 ± 25.06) compared to TF (49.58 ± 27.91) but without a significant difference ($p = 0.14$). The participants felt they can complete the task without much temporal demand (TE: 36.67 ± 25.61; TF: 37.59 ± 21.90; TE vs. TF, $p = 0.87$) and performance failure (TE: 42.08 ± 27.83; TF: 34.16 ± 26.69; TE vs. TF, $p = 0.31$) using both grasping strategies. The two grasping modes also showed no significant effect on *effort* and *frustration* (all $p > 0.5$).

When the participants rank two interfaces after the tasks, 9 of 12 participants selected the interaction strategy with the toe extension gesture and interface 2; while only 3 of them prefer TF and interface 3. The participants commented that TE is more easy, natural and intuitive to control, especially to exert and maintain the force while grasping.

VI. DISCUSSION

We proposed a systematic selection process to identify effective foot control strategies for grasping the DoF of a surgical tool. The selection process firstly considered the users' opinions on the difficulty of the possible foot gestures, and four gestures with toes were found by participants as easy to achieve. The independent control capability study then evaluated the foot control coupling between motion and grasping and it was found that gestures of TE and TF which do not directly exert force on the pedal were less affected by foot motion commands and are more robust to motion noise than MP and BP. TE and TF control strategies integrated with the pedal interface finally proved to be valid command inputs for the control of a virtual laparoscopic instrument. Although we did not find any differences in performance and perceived workload for these two gestures, the interaction mode with TE was the preferred strategy for most the participants. In addition, we presented three modular foot-machine interfaces for collecting foot pressure gestures. Those interfaces can be adjusted for different foot autonomy and easily integrated into other motion control interfaces.

We observed a large variation between subjects during the whole selection process for both subjective responses and objective control performance. Our present approach mainly analysed the trend of all participants based on the provided gestures. A possible future improvement of this study is to identify users' individual control patterns and identify customized grasping control strategies. Furthermore, the users' operation performance of different gestures may also be affected by the design of different grasping interfaces. We will investigate intuitive and comfortable interaction strategies in the future with the development of new interfaces, and conduct systematic comparison and evaluation of different kinds of interaction strategies.

ACKNOWLEDGMENT

We thank the subjects for participating in the experiment.

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