A subject-specific four-degree-of-freedom foot interface to control a surgical robot

Huang, Yanpei; Burdet, Etienne; Cao, Lin; Phan, Phuoc Thien; Tiong, Anthony Meng Huat; Phee, Soo Jay

2020

Huang, Y., Burdet, E., Cao, L., Phan, P. T., Tiong, A. M. H., & Phee, S. J. (2020). A subject-specific four-degree-of-freedom foot interface to control a surgical robot. IEEE/ASME Transactions on Mechatronics, in press. doi:10.1109/tmech.2020.2964295

<https://hdl.handle.net/10356/137939>

<https://doi.org/10.1109/TMECH.2020.2964295>

© 2019 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at: <https://doi.org/10.1109/TMECH.2020.2964295>

Downloaded on 26 Apr 2023 19:48:03 SGT

A subject-specific four-degree-of-freedom foot interface to control a surgical robot

Yanpei Huang¹, Etienne Burdet^{2*}, Lin Cao^{1*}, Phuoc Thien Phan³, Anthony Meng Huat Tiong¹
and Soo Jay Phee¹

Abstract—This paper introduces a passive four-degree-of-freedom foot interface to control a robotic surgical instrument. This interface is based on a parallel-serial hybrid mechanism with springs and force sensors. In contrast to existing switch-based interfaces that can command a slave robot arm at constant speeds in only discrete directions, the novel interface provides an operator with intuitive control in continuous directions and speeds with force and position feedback. The output command of the interface was initially derived based on the kinematics and statics of the interface. Since distinct movement patterns among different subjects were observed in a pilot test, a data-driven approach using Independent Component Analysis was developed to convert the foot inputs to the control commands of the user. The capability of this interface in controlling a robotic arm in multiple degrees of freedom was further verified with a teleoperation test.

Index Terms—Human-machine interaction, foot interface, surgical robots, subject-specific control.

I. INTRODUCTION

HUMAN-MACHINE interfaces (HMI) are important components of teleoperation systems. Some commercial hand-controlled HMIs, such as the Phantom (3D Systems, US) and Omega/Sigma haptic devices (Force Dimension, Switzerland), can be used as master devices to telemanipulate remote robotic arms. For example, the RAVEN robotic system [1] includes the Phantom Omni hand interface for teleoperation and haptic feedback; the MiroSurge [2] uses the Sigma 7; the Da Vinci system [3] is equipped with a built-in master console through which the surgeon can telemanipulate and switch instruments.

These HMIs provide sufficient manipulation control with two hands; however, many surgical operations require three or more instruments simultaneously. Traditionally, a human assistant controls the additional instruments in coordination with the surgeon. For instance, an assistant can adjust the camera's field of view during laparoscopic surgery; in a robotic flexible endoscopic surgery, the robotic arms controlled by the surgeon can only work in a small workspace and thus an endoscopist is needed to move the endoscope which is carrying the robotic arms to adjust the working area [4], [5]. The necessity to collaborate with an assistant may create issues, as

surgical performance and efficiency are often limited by the communication delays and errors between the surgeon and the assistant [6].

A solution to address this issue is to let the surgeon control the additional instruments [7]. Various hand-free interfaces have been developed to control the camera of laparoscopic surgery using head movement [8], voice [9], or switches activated by fingers or feet [10], [11]. However, most of these interfaces have intrinsic limitations. For instance, turning the head away from the area of interest may affect hand movements; noise in the operation room may interfere with voice command, and several people cannot send voice commands simultaneously; finger movements are coupled with the hand movements.

Foot controlled movements are easy to learn [12], can be used in conjunction with hand movements [13], [14], and may provide similar or better skill as compared to hand/voice controlled movements [15], [16]. Therefore may be a good modality for inputs when the user's hands are busy [17]. Either foot position or force can be used to detect desired commands. Using foot motion is more intuitive but may require large movements of the leg and thus lead to fatigue [18]. The foot force/pressure can be measured instead, e.g., using in-shoe pressure sensors, potentially allowing fine motion control over a large workspace [19], [20], although it may be non-intuitive to use the force for movement control [21]. Using a foot support dragging on the ground can reduce the effort against gravity but it introduces friction [22]. Foot rotations like ankle dorsiflexion/planar-flexion and lateral/medial rotation are used in vehicle driving and selection tasks [23]. In general, it is still unclear how to best use foot movements to teleoperate a robot.

Representative foot interfaces for controlling multiple-DoF motions in surgery are summarized in Table I. Commercially available foot interfaces [24]–[26] mainly consist of switches and buttons closely placed on a planar base to command the surgical tool at constant speeds in various single-axis directions. Such an interface is simple to control but may not be suitable for complicated manipulation motions (especially with more than three DoFs). Furthermore, the need to lift the leg up and down can cause fatigue during long operations [22]. Most of these interfaces provide neither positioning assistance nor force feedback, thus may require the operator to visually check the foot posture frequently. Abdi et al. [27] developed two foot interfaces to manipulate a laparoscopic camera in four DoFs with the foot at rest. The elastic-isometric interface was preferred by operators than the isotonic interface, as the

¹Authors are or were with the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. ²Etienne Burdet is with the Department of Bioengineering, Imperial College of Science Technology and Medicine, London, UK. ³Phuoc Thien Phan is with Graduate School of Biomedical Engineering, University of New South Wales, Sydney, Australia. *Corresponding authors' email address: e.burdet@imperial.ac.uk; lin.cao@ntu.edu.sg.

TABLE I
CHARACTERISTICS OF FOOT INTERFACES FOR ROBOTIC SURGERY.

Denomination	DoF	Input mode	Control mode	Positioning & resting	Force feedback	Individual adaptation
AESOP [11], [24]	3	continuous, force	single axis, pressure proportional speed	✗	✗	✗
ViKy [25]	3	binary	single axis, constant speed	✗	✗	✗
RoboLens [26]	3	binary	single axis, constant speed	✗	✗	✗
HIWIN [30]	3	binary	single axis, constant speed	✓	✗	✗
Elastic-isometric interface [27]	4	continuous, force	single axis, constant speed	✓	✓	✗
Isotonic interface [27]	4	continuous, position	combined in four-DoF, position	✓	✓	✗
Proposed interface	4	continuous, position and force	combined in four-DoF, pressure proportional speed	✓	✓	✓

✓ / ✗ means that a device has / does not have a corresponding feature ; Binary input is either 0 or 1.

former one requires less effort and provides accurate control with passive elastic feedback. However this passive feedback offered only indicates the contact status but not the force levels, and it could only be used to command one direction at a time. Overall, the passive interfaces [28], [29] can provide sufficient force feedback and assistance to the operator when the elastic elements are properly arranged.

This paper introduces a foot interface overcoming the limitations of the previous interfaces (see Table I). The novel four-DoF passive interface enables an operator to control a slave robotic arm with continuously changing directions and speeds. The parallel-serial hybrid mechanism of this interface is conceived to pick up natural foot movements and integrates a ground support that reduces fatigue. Specially designed modules provide simultaneous force and position sensing and feedback for skillful control with an unlimited force range in a small foot movement range (less fatigue). In view of distinct motion behaviour of each subject, a data-driven technique is developed to adapt the interface to the specific user's motion patterns which effectively filters out unintended foot motions.

The paper is organized as follows: Section II describes the selection of four-DoF foot motions, and determines the interface's operation modes. Section III presents the interface's design concept. Section IV examines how to map the foot force to control commands using kinematic and data-driven mappings. Section V describes two experiments to test the mapping methods and validate how the interface can be used to teleoperate a robot in the typical tasks of surgical training. Section VI analyzes the result and summarizes the paper's contributions. Section VII presents the conclusion.

II. WORKING PRINCIPLE OF THE INTERFACE

The proposed foot interface (described in Section II-A) is designed to: *i*) map the natural foot motions as directly as possible to the laparoscopic tool movements, and *ii*) minimise fatigue, while *iii*) providing concurrent position and force sensing & feedback using dedicated passive modules. These modules (Section II-B) should: *i*) sense both position and force inputs in a small workspace with force that is limited only by the operator's abilities; *ii*) facilitate accurate and comfortable foot motion through a compliant interaction; *iii*) provide automatic homing assistance; *iv*) without singularities in the workspace.

A. Foot movements to control a laparoscopic tool

The conventional laparoscopic tool, e.g. a laparoscopic camera, use four-DoF positioning (Fig. 1a, [31]): in/out translation, two rotations around the trocar at the incision of the abdominal wall, and rotation around the longitudinal axis of the tool. The three rotations can be conducted in a curved plane around the pivot point, and the in/out translation can be controlled separately. Correspondingly, humans can rotate the shank around the knee, leading to foot translations and rotation in the horizontal plane. Four-DoF specific foot motions (Fig. 1b) were selected to provide an intuitive mapping to control the laparoscopic tool: *i*) foot forward/backward movements (caused by knee joint flexion/extension) control the pitch of the tool, *ii*) foot lateral movements (due to hip's abduction/adduction) control the yaw of the tool, *iii*) foot lateral/medial axial rotation maps to the roll of the tool, *iv*) the dorsi/planta-flexion of the ankle controls the in/out translation of the tool. This arrangement avoids lifting up and down the whole leg, which, otherwise, can be tiring for the operator [22].

A relatively small workspace has been set to avoid uncomfortable operation and human fatigue. Specifically motions *i*) and *ii*) are limited to 2cm; *iii*) is maintained within 12.5° and *iv*) within 10°. Further, fatigue can be minimised by letting the foot be supported by the interface.

B. Feedback-sensing modules

The feedback-sensing modules can then be placed around the foot to collect the above foot gestures (Fig. 1c). Each feedback-sensing module consists of an elastic element set against a force sensor, as illustrated in Fig. 2. The mobile part is activated by foot movements whilst the elastic element is deformed under the force of the foot motion/force detected by the force sensor. The measured forces can then be used to calculate the deformations of the elastic module which are used to calculate the position and orientation of the mobile part through its kinematics. The whole foot operation is separated into an elastic mode (Fig. 2a) and an isometric mode (Figs. 2b,c). Within the elastic element's motion range, the foot is free to move (with reaction forces from the springs), and the position/force of the foot can be used as output of the interface to control a robotic arm; this yields the *elastic control mode*. Once the elastic element reaches the elastic

Fig. 1. Mapping natural foot motions to control the four-DoF laparoscopic instrument. (a) Movements of the laparoscopic instrument. (b) Corresponding foot movements. (c) Placement of the feedback-sensing modules.

Fig. 2. Feedback-sensing module in elastic mode (a) and in isometric modes (b,c). v : velocity, F_e : force exerted by the foot, F_s : elastic force, F_r : reaction force.

limit (e.g. the fully compressed compression spring in Fig. 2b) or mechanical constraint (Fig. 2c), the foot cannot move beyond the boundary, but the force can still be increased by the user. This force signal yields the *isometric control mode*. The continuous transition of the elastic and isometric modes creates an interaction providing rich proprioceptive information to the operator with a force range limited only by his/her strength.

III. INTERFACE DESIGN

A. Design overview

The interface is designed as a parallel-serial hybrid mechanism controlled by foot interacting with a pedal. Foot motions drive the pedal and mobile frame (MF) resulting in sliding in the horizontal plane in two translations x, y and one rotation ϕ (2T1R) in a parallel structure with six feedback-sensing modules integrating a compression spring and a load cell (Fig. 3a). The pitch rotation θ of the pedal is activated by foot dorsi/plantar-flexion, which is decoupled from the horizontal movements through an extended serial structure with two feedback-sensing modules integrating a torsion spring and a load cell (Fig. 3b). The parallel mechanism provides a simple and compact structure with low inertia and high accuracy through closed-loop kinematics. The serially connected pedal provides a relatively large space for the foot to control the in/out translation of the laparoscopic tool.

The elastic mode of the system is achieved through the elastic network with eight springs providing dynamic real-time passive force and position feedback. The usage of force

sensors instead of position sensors collects force information of the operator's foot within and even beyond the geometric workspace, enabling transition between the elastic and isometric modes. The isometric mode can be activated either by the fully compressed compression spring (Fig. 3a) or by mechanical constraint (e.g. in Fig. 3b, θ reach the largest value when the moving block hit the fixing block).

The springs in our system are carefully arranged to provide a singularity-free workspace with a neutral central home position (global minimum elastic energy), shown as solid lines of the pedal in Fig. 3a. Fig. 3c illustrates a naive design with the compression springs placed between the base and the pedal. This design yields two singular configurations at the extreme yaw rotations, where the pedal remains twisted, making the pedal's movement uncontrollable. This issue was addressed by placing the compression springs outside of the base (Fig. 3a). The elastic energy has a unique global minimum value at the home position (Fig. 3d). When the operator finishes operation movements and releases the pedal, the interface returns to the home position automatically (assuming zero friction), providing positioning assistance, a resting posture for the foot and enabling a quick start for the next operations, without the need of a visual check.

B. Foot interface structure

The 3D model of the foot interface is presented in Fig. 4. The interface includes a base which is fixed on the ground, a mobile frame, a pedal with an adjustable foot fixture and the feedback-sensing module with the spring and force sensor. The base and the MF are assembled in a parallel structure, connected with six guides and pivot joints (Fig. 4a). The corresponding feedback-sensing modules are assembled on the guides (Fig. 4c). The MF and the pedals' structure is shown in Fig. 4b. The pedal plate for the foot is serially mounted on the mobile frame with a pivot shaft and two vertically placed feedback-sensing modules (Fig. 4d), acting as an input component for pitch rotation θ . An adjustable fixture mechanism (Figs. 4a,b) yields a comfortable but rigid foot fixation. This fixture is composed of four 3D-printed foot-

Fig. 3. Passive four-DoF foot interface. The schematic diagram in (a) top view and (b) side view at home position (dotted lines show a random position of the pedal). (c) A naive design (not selected in this study) with singularities and unstable configurations and (d) the elastic energy distribution with ϕ for spring arrangement in (a) and (c).

shape blocks that can be adapted to feet of sizes from 35 to 46 in the European standard using guide screws.

C. Friction reduction

Four universal wheels are mounted at the bottom of the mobile plate (Fig. 4b) to reduce friction. Linear bearings are mounted on the guide rods to minimise the sliding friction between the guide rod and the O-shaft (Fig. 4c). The O-shaft and the base are connected through hinge joints with radial bearings. Furthermore, considering the parallel structure of the foot's planar movements, the dynamically changing pressure accompanying the foot movement causes small vertical fluctuations that may lead to radial forces and resistance in the axial motion. Ball joint rod end bearings (connecting each guide rod with the mobile frame, Fig. 4c) and radial spherical plane bearings (assembled in the O-shaft around linear bearing, Fig. 4c) allow vertical movement and avoid resistance due to vertical fluctuations. The friction coefficient of the system is small (about 0.018 to 0.026).

D. Elastic elements and sensors

The six compression springs and a pair of torsion springs form a spring network with four DoFs:

a) Compression spring: Springs of different stiffness $\{0.01, 0.02, 0.03, 0.05, 0.1\}$ N/cm were tested, and the 0.02 N/cm compression spring was selected as it was not too hard to press while providing sufficient haptic feedback. Compression rather than extension springs were used because compression springs allow force measurement by the load cells even when fully compressed and they are simple to assemble. In this study, springs with constant stiffness were considered for proof of concept; in future studies, optimally designed compliant

structures [32]–[34] with desired stiffness characteristics (e.g., nonlinear stiffness) maybe used to replace these springs for better interactions between the foot and the interface.

b) Torsion spring: A pair of torsion springs with 46.3 Ncm/° stiffness was selected for the pitch DoF in order to provide an elastic force with the pedal rotation. The torsion springs are mounted symmetrically but in the reverse direction around the pivot rotation shaft which supports the pedal plate. The lower fixed arm is horizontally placed as a reference arm. The torsion springs do not directly contact the shaft leaving a rotation margin, as the inner diameter of the torsion spring changes a little during operation (Fig. 4d). The v-shape lock and the slot on the load cell tray are designed to fix and avoid noisy shaking of the torsion spring's upper limb in radial and axial translation. The maximum twisting angle of the pedal plate (from the initial position) was mechanically limited to $\pm 10^\circ$. This can be reached once the stopper (moved with the pedal plate) is touching the vertical plane of the pivot shaft seat (Fig. 4d).

c) Sensing: The forces applied by the operator are translated into electrical signals through eight force sensors (LW1025-25 from Interface, Inc., USA). To ensure that the springs can effectively transmit forces to the load cells in any poses of the pedal, a 5.6 N pre-compression and a 57 N pre-tension force are applied for each compression spring and torsion spring respectively at home position. While the pedal's movement is limited by the deflection range of the compression spring (for DoFs in 2T1R) and mechanical constraint (for DoF in pitch rotation), the force detection range is not restrained, i.e., once a compression spring is fully compressed, or the pitch rotation reaches the limit angle, the isometric force continues to build up and is therefore still measured by the load cell.

Fig. 4. 3D structure of the foot interface. Perspective view (a) and mobile frame and pedals' side view (b). Explosive views of compression spring feedback-sensing module (c) and torsion spring feedback-sensing module (d).

IV. COMPUTATION OF MOTOR COMMANDS

In this section, a kinematic model of the novel interface is first derived in Section IV-A. This direct kinematic model can be used to compute how the foot movements can be translated to external commands in elastic mode. A static model is then derived in Section IV-B, which can be used to compute the motor command from the applied forces in isometric mode. Alternatively to this analytical model, it is possible to identify a mapping from the eight force sensors to the intended motor command directly from the data of a specific operator. Such a data-driven approach using Independent Component Analysis (ICA) is developed in section IV-C.

A. Kinematics

The kinematics of the three DoFs of 2T1R can be simplified as planar movements within a 6-RPR planar parallel mechanism as shown in Fig. 3a in which the pedal is constrained and connected to the base with six guides with hinge joints on both sides (represented as points A_i on the base and B_i on the MF). A fixed base reference frame $\{O-xy\}$ and mobile reference frame $\{C-x'y'\}$ are assigned to the centroid of the base and the MF square plane, respectively.

The position vector of point A_i is defined by the vector $\mathbf{a}_i \equiv [a_{ix}, a_{iy}]^T$ expressed in the fixed frame $\{O\}$ whereas the position vector of point B_i is defined as $\mathbf{b}_i \equiv [b_{ix}, b_{iy}]^T$ in the mobile frame $\{C\}$. They can be represented using a, b, a', b' , the lengths and widths of base and the MF square, and e, e' ,

the distance between the laterally located linear spring guides, equal to lengths A_3A_5 and B_3B_5 . The position of the MF reference frame $\{C\}$ relative to the base reference frame $\{O\}$ is defined by the vector $\mathbf{p} = [x, y]^T$ connecting O to C , while its orientation is defined by the angle ϕ between the $\hat{x}_O$ axis of the $\{O\}$ and the $\hat{x}'_C$ axis of the $\{C\}$. The length of i th spring guide between the attach points of base A_i and the MF B_i is denoted as L_i . Finally, let $\mathbf{u}_i \equiv \overrightarrow{B_iA_i}/L_i$ denote the unit vector along i th spring guide, and $\mathbf{L}_i \equiv L_i\mathbf{u}_i$.

Using these definitions, the closed mechanical chain of Fig. 5a can be expressed as

$$\mathbf{L}_i = \mathbf{a}_i - \mathbf{p} - \mathbf{R}\mathbf{b}_i, \quad \mathbf{R} \equiv \begin{bmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{bmatrix}, \quad (1)$$

where $\mathbf{R}(\phi)$ is the rotation matrix from the fixed frame $\{O\}$ to the mobile frame $\{C\}$. For this parallel mechanism, the *inverse kinematics*, i.e., calculating the guide lengths L_i as a function of the pose translation $\mathbf{p} = [x, y]^T$ and rotation ϕ , can be computed from the closure constraints:

$$L_i^2 = (x + b_{ix}c - b_{iy}s - a_{ix})^2 + (y + b_{ix}s + b_{iy}c - a_{iy})^2 \quad (2)$$

where $c \equiv \cos \phi$ and $s \equiv \sin \phi$. For the *forward kinematics*, given $\{L_i, i = 1, 2, \dots, 6\}$, $\mathbf{X} = [x, y, \phi]^T$ can be derived by solving the six scalar equations (2), yielding

Fig. 5. (a) Kinematic model of i th compression spring and (b) statics forces in x - y horizontal plane and (c) pitch rotation DoF.

$$\begin{aligned}
 x &= \frac{F(a'\sqrt{4P^2 - E^2} - 2aP) - 2bEG}{4Q\sqrt{4P^2 - E^2} - 8PM} \\
 y &= \frac{2G(b'\sqrt{4P^2 - E^2} - 2bP) + a'EF}{4Q\sqrt{4P^2 - E^2} - 8PM} \\
 \phi &= \arcsin \frac{E}{2P}, \quad P \equiv be' - b'e \\
 E &\equiv L_4^2 + L_5^2 - L_3^2 - L_6^2, \quad F \equiv L_3^2 + L_5^2 - L_4^2 - L_6^2, \\
 G &\equiv L_2^2 - L_1^2, \quad M \equiv ab + a'b', \quad Q \equiv ab' + a'b.
 \end{aligned} \quad (3)$$

The magnitude of the guide length L_i is derived from the delta compression spring forces via Hooke's Law:

$$L_i = L_{0i} + \frac{\Delta f_i}{k_i}, \quad \Delta f_i = f_i - f_{0i}, \quad i = 1, 2, \dots, 6, \quad (4)$$

where k_i is the compression spring stiffness constant of i th spring. L_{0i} , f_{0i} are the original length and pretension force of i th spring guide and spring at home position, respectively. f_i is i th load cell's reading. The pitch rotation angle is

$$\theta = \frac{M_x}{K_p}, \quad (5)$$

where M_x , K_p are the rotation torque and stiffness constant in pitch DoF which will be derived in eq.(9).

B. Statics

With the force analysis in the horizontal plane of Fig. 5b, the resultant elastic force and torque of $\mathbf{F}_R$ and $\mathbf{M}_z$ can be computed from the compression spring forces $\mathbf{f}_i = f_i \mathbf{u}_i$, $i = 1, 2, \dots, 6$. The corresponding statics equations are:

$$\begin{aligned}
 \mathbf{F}_R &= \sum_{i=1}^6 \mathbf{f}_i, \\
 \mathbf{M}_z &= \sum_{i=1}^6 \mathbf{f}_i \times \mathbf{R} \mathbf{b}_i = \sum_{i=1}^6 \det(\mathbf{f}_i, \mathbf{R} \mathbf{b}_i),
 \end{aligned} \quad (6)$$

which can be summarized in matrix form as

$$\begin{aligned}
 \mathbf{W}_R &= \mathbf{J} \mathbf{f}, \quad \mathbf{f} \equiv \begin{bmatrix} f_1 \\ \vdots \\ f_6 \end{bmatrix}, \quad \mathbf{W}_R \equiv \begin{bmatrix} \mathbf{F}_{xR} \\ \mathbf{F}_{yR} \\ \mathbf{M}_z \end{bmatrix}, \\
 \mathbf{J} &= \begin{bmatrix} \mathbf{u}_1, \dots, \mathbf{u}_6 \\ \det(\mathbf{u}_1, \mathbf{R} \mathbf{b}_1), \dots, \det(\mathbf{u}_6, \mathbf{R} \mathbf{b}_6) \end{bmatrix},
 \end{aligned} \quad (7)$$

where $\mathbf{J}$ is the structure matrix of the planar parallel structure. The stiffness matrix $\mathbf{K}$ in the motion workspace can be found by taking derivatives of $\mathbf{W}_R$ with respect to $\mathbf{X}$:

$$\begin{aligned}
 \mathbf{K} &= \frac{d\mathbf{W}_R}{d\mathbf{X}} = \mathbf{J} \frac{d\mathbf{f}}{d\mathbf{X}} + \frac{d\mathbf{J}}{d\mathbf{X}} \mathbf{f} = \mathbf{J} \mathbf{C} \mathbf{J}^T + \frac{d\mathbf{J}}{d\mathbf{X}} \mathbf{f}, \\
 \mathbf{C} &\equiv \text{diag}(k_1 \dots k_6).
 \end{aligned} \quad (8)$$

The torque for the pitch rotation M_x around the center point C is obtained through the following equation:

$$M_x = f_7 b_7 - f_8 b_8, \quad K_p = \begin{cases} k_7 & \text{if } M_x > 0 \\ k_8 & \text{if } M_x < 0 \end{cases} \quad (9)$$

where f_7 and f_8 are tension force calculated from readings of load cells 7 and 8 (Fig. 5c). b_7 and b_8 are the arm lengths from pedal plate center C to positions of load cells 7 and 8, which can be modified according to the operators' habitual posture. The stiffness K_p in this DoF is directly reflected in k_7, k_8 , the stiffness constants of torsion springs 7 and 8, respectively.

The $\mathbf{J}_s$ and $\mathbf{K}_s$ of the four-DoF structure can then be rewritten as:

$$\begin{aligned}
 \mathbf{W} &= \mathbf{J}_s \mathbf{f}, \quad \mathbf{f} = \begin{bmatrix} f_1 \\ \vdots \\ f_8 \end{bmatrix}, \quad \mathbf{W} = \begin{bmatrix} \mathbf{F}_{xR} \\ \mathbf{F}_{yR} \\ \mathbf{M}_z \\ \mathbf{M}_x \end{bmatrix}, \\
 \mathbf{J}_s &= \begin{bmatrix} \mathbf{J} & \mathbf{0} \\ \mathbf{0} & \mathbf{J}_p \end{bmatrix}, \quad \mathbf{J}_p = [b_7, -b_8], \quad \mathbf{K}_s = \begin{bmatrix} \mathbf{K} & \mathbf{0} \\ \mathbf{0} & K_p \end{bmatrix}.
 \end{aligned} \quad (10)$$

where the resultant wrench $\mathbf{W}$ is the feedback to the human.

C. Data-driven approach to compute the motor command

The forces measured by the interface will reflect the operator's foot motion intention and can be used to control a

device with four DoFs. To do so, a mapping from the eight load cell force signals to a movement in the four DoFs of $\mathbf{D} \equiv \{x, y, \phi, \theta\}$ is needed, reflecting the pose of center point C of the pedal under the base frame $\{O\}$ (Fig. 3a). An obvious solution consists of using the forward kinematics and statics as developed in previous two sections. An alternative idea consists of identifying direction specific force patterns of an operator and using them to compute the motor commands.

In this data-driven approach, a calibration procedure is first conducted to collect single axis Cartesian motion data of left (L) & right (R), forward (F) & backward (B), left torsion (LT) & right torsion (RT), toe up rotation (TU) & toe down rotation (TD). Each pair of the force data is used as input to the ICA model in order to derive corresponding mapping coefficients for each DoF, represented as $\mathbf{T}_x, \mathbf{T}_y, \mathbf{T}_\phi, \mathbf{T}_\theta$. These coefficients form the 4×8 mapping matrix $\mathbf{T}$ reflecting the new basis of four-DoF for the specific subject in the combination of eight load cells' readings, with equations

$$\mathbf{D} = \mathbf{T} \mathbf{f}_n, \quad \mathbf{D} \equiv \begin{bmatrix} x \\ y \\ \phi \\ \theta \end{bmatrix}, \quad \mathbf{T} \equiv \begin{bmatrix} \mathbf{T}_x \\ \mathbf{T}_y \\ \mathbf{T}_\phi \\ \mathbf{T}_\theta \end{bmatrix},$$

$$\mathbf{f}_n = \frac{\mathbf{f} - \bar{\mathbf{f}}}{\sigma}, \quad \mathbf{f} \equiv \begin{bmatrix} f_1 - f_{01} \\ f_2 - f_{02} \\ \vdots \\ f_8 - f_{08} \end{bmatrix}, \quad (11)$$

where $\mathbf{f}_n$ is the z-score normalization form of delta force changes of the load cells' readings. The FastICA algorithm [35] is then applied onto this data to derive a subject-specific ICA model. The control command $\mathbf{D}$ is derived from the mapping matrix and the load cells' readings.

V. EXPERIMENTS

Two experiments were conducted. The first experiment was to investigate the subject-specific foot motion pattern, and the second experiment was to validate the use of the novel foot interface in a teleoperation system for controlling a robot. The experiments were approved by the Institutional Review Board (IRB) of Nanyang Technological University (IRB-2018-05-051).

A. Experiment 1: Human motion intention and motion pattern

A pilot experiment was conducted with ten subjects (27.3 ± 2.2 years old, right foot dominant, 4 females) to study the precision with which they can control the interface in given directions using their dominant foot.

1) *Experiment procedure*: The subjects were seated comfortably on a chair in front of a table, and the foot interface was placed under the table at the home position. Each subject was asked to step their right foot on the pedal and adjust the positions of the fixture blocks to match his/her specific foot size. The *task* was to move the pedal from the home position along multiple specified directions 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. The task was demonstrated to the subjects by the experimenter prior to data collection. The subjects were also informed of the desired target directions. No visual feedback of the foot posture was provided during the experiment. In this way, we could observe feedforward foot movements corresponding to any desired motion directions. Movements were carried out in single and diagonal directions:

a) *Single directions*: Each subject started at the home position. Three trials were conducted in each of the following 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) in this order. This procedure was continuous without pause until all the $3 \times 8 = 24$ centre-out and back movements were completed. Then, the subject lifted down their foot and took a 30 seconds' break. Another group of 24 trials was repeated after that.

b) *Common diagonal directions*: Each subject started at the home position. Three trials were conducted in the twelve common diagonal directions, which are the combination of the two single Cartesian directions, in the order of {left & forward (LF), right & forward (RF), left & backward (LB), right & backward (RB), left & toe up (LTU), right & toe up (RTU), left & toe down (LTD), right & toe down (RTD), forward & toe up (FTU), backward & toe up (BTU), forward & toe down (FTD), backward & toe down (BTD)}. $3 \times 12 = 36$ trials were conducted in diagonal directions.

2) *Performance measure*: Foot force data from load cells were recorded at 50Hz and smoothed offline by using a moving average filter with window size of 9. Then the force data were mapped to the pose vector $\mathbf{D} = [x, y, \phi, \theta]^T$ of the center point C on the pedal using the forward kinematics Eqs.(3, 5). The actual initial position of the foot interface for each consecutive operation was considered as the calibrated home position.

To compare different components of the pose, a point P on the pedal, $\mathbf{P} = [0, d, 0, 0]$ (with $d=11.5\text{cm}$) with respect to $\{C\}$, was selected as a reference point (see Figs. 5b,c). The four-DoF position change of point P with respect to home position is represented as $\mathbf{P} = [P_x, P_y, P_\phi, P_\theta]$, where $P_x = x$, $P_y = y$, $P_\phi^2 = (d \sin \phi)^2 + (d - d \cos \phi)^2$, $P_\theta = d \sin \theta$, with the range $P_x, P_y, P_\theta \in [-2, 2]\text{cm}$, $P_\phi \in [-2.5, 2.5]\text{cm}$. A scaling factor $s=2/2.5$ was used for P_ϕ to bring the two angles into the same range. The data of vector $\mathbf{P}$ was then filtered to remove the static position data using a resultant velocity threshold of 0.005m/s.

Foot-path error was used to quantify the performance in the trials,

$$E = \frac{1}{N} \sum_{i=1}^N \|\mathbf{e}_i\|, \quad \mathbf{e}_i \equiv \mathbf{p}_i - \hat{\mathbf{p}}_i = [e_{ix}, e_{iy}, e_{i\phi}, e_{i\theta}], \quad (12)$$

where $\mathbf{p}_i$ is the real trajectory points, $\hat{\mathbf{p}}_i$ the projection of $\mathbf{p}_i$ on the desired path, and N is the total number of samples for foot movements in each direction.

B. Experiment 2: Teleoperation

Four subjects (28.5 ± 3.3 years old, right foot dominant, 2 female) participated in the second experiment. A teleoperation

Fig. 6. Teleoperation system with (a) foot operating the novel interface, (b) slave robot and (c)(d) tasks setup.

system was built up using the proposed foot interface to command an industrial robot (IRB120, ABB robotics). The four-DoF motion of the foot in x, y, θ, ϕ are collected by the foot interface (Fig. 6a), which are used to control the speed of the robot in x_t, y_t, z_t, ϕ_t (Fig. 6b). Three videos of these experiments are provided as supplementary materials ¹.

Two tasks were used to test complex multi-DoF manipulation and speed control for accurate positioning, respectively. The experiment consisted of three phases: *i*) Calibration as described in the single direction task of Section V-A, *ii*) Practice for five minutes, and *iii*) Testing consisting of the two tasks described below. At the end of this testing, the user answered the questionnaires to estimate the workload.

1) *Task 1: Spatial coordination*: The first task consisted of following the 2D wire (of diameter 0.25cm, shown in Fig. 6c) with a ring (with inner diameter 0.8cm). The wire (fixed on a platform) has straight, curved, and diagonal sections. The ring is fixed to the robot end-effector and around the wire. It is initially placed at one end of the wire. The operator has to control it in x_t, y_t and ϕ_t and follow the wire without collision. One trial is completed when the tool reaches the other end of the wire. The trial is failed if a collision is detected and the robot then stops.

Two subjects started with ICA and the other with the kinematics mapping, but the subjects were not aware of the mapping method. Each subject conducted two successful trials with each mapping. A small zero band was defined in each DoF using the calibration modeling data, the upper and lower limits in translation x, y and rotation ϕ, θ were identified as the 30% of the respective maximum and minimum values of the modeling data's mapping results in kinematics and ICA. The ranges are: $[-0.6, 0.6]$ cm for x, y , $[-4^\circ, 4^\circ]$ for ϕ , $[-3^\circ, 3^\circ]$ for θ when reported in the kinematic model. If a mapping's result falls into the zero band, it is regarded as zero output in the responding DoF. The robot speed was set at 0.6cm/s.

2) *Task 2: Temporal coordination*: The second task required three DoFs control for accurate positioning. As shown in Fig. 6d, five LED buttons with different heights are placed

on a platform. The diameter of the pressing area of each button is 0.9cm. The robot end-effector is equipped with a pressing tool with a compliant ending and a tool tip of 0.6cm diameter. The operator had to move the pressing tool in x_t, y_t and z_t and press a sequence of red lightened LED one by one without touching the aluminum button base.

The tool was located 5cm above the middle LED button at the initial position. Each trial included three sequentially random lighted LEDs, and each subject was required to conduct ten trials. Only the ICA mapping was used in this task to test speed control. The robot velocity was set proportional to the force exerted by the foot, with the maximum robot velocity of 3cm/s corresponding to 1.5 times the elastic-isometric boundary force.

3) *Subjects' evaluation*: Subjective evaluation of the interface was carried out using the NASA Task Load Index [36] which is a robust method to measure the subjective workload. Six factors are considered: Mental, physical, temporal demands, performance, effort and frustration, to estimate the overall workload, based on subjective answers. The assessment is carried out in two steps: the subjects first mark each factor (on a $\{0, 5, 10, \dots, 100\}$ scale in a questionnaire), then evaluate the contribution of each factor (by comparing these six factors in 15 pairs in a second questionnaire).

VI. RESULTS AND DISCUSSION

A. Experiment 1: Human motion intention and motion pattern

1) *Subject-specific control pattern*: Fig. 7 shows the foot-path error E over the ten subjects in various directions and the variability over the consecutive trials of each subject. For single directions, LT and RT have a larger error relatively to the other directions (Figs. 7a,b), and translations in F/B and L/R have less errors and deviations than rotations. Diagonal directions (Fig. 7c) that combine translations in $x-y$ planes have less error than the diagonal motions involving rotation and translation in the $x-\theta$ and $y-\theta$ planes.

In most cases, the deviation is large between subjects. On the other hand the deviation is relatively small in the trials of each single subject, especially in single directions. There is no significant difference between the two single data sets for the average deviation within trials (t-test, $p=0.47$),

¹Movie 1 shows the robot operated by the foot in various directions using the ICA mapping. Movie 2 shows a subject carrying out Task 1. Movie 3 shows a subject carrying out Task 2.

Fig. 7. Foot-path error and its standard deviation over subjects and consecutive trials for each subject on (a) data set 1 of single-direction trials, (b) data set 2 of single-direction trial and (c) data set 3 of diagonal-direction trials.

Fig. 8. Foot path error using the ICA/kinematics model applied on: (a) the single Cartesian modeling data, (b) the single Cartesian testing data, and (c) the diagonal directions testing data.

meaning that there was no learning effect between these two periods. However, the movements in diagonal directions has larger deviation within trials than the single directions (t-test, $p < 0.014$).

2) *Evaluation of motion intention with analytical and data-driven mappings*: Using the analytical approach via the kinematics and statics mapping (of Sections IV-A and IV-B) to command a motion direction, we see in Fig. 7 that the variability between different subjects is large, while the variability over consecutive trials of a single subject is relatively low.

Therefore, it may be preferable to generate commands corresponding to each subject's habitual foot motion characteristics, corresponding to the data-driven approach of Section IV-C. Once a subject-specific model is built using the calibration procedure described in the single direction task of section V-A, the subject-specific patterns are used online to interpret new control inputs.

To test this method, we analysed the three sets of data collected in Section V-A that are used for modeling (single axis direction data set 1) and testing (single axis direction

data set 2 and diagonal axis direction data). The *foot path error* (Eq.12) is computed for subjects and directions to check the accuracy of the control commands using both methods. For comparison purposes, the results from the ICA and kinematics method are converted to the range $[-1,1]$ through a min-max normalization. The ϕ DoF is not considered in the diagonal direction analysis: As it cannot reach the extreme value during diagonal motions, the normalized data cannot be compared with the other DoFs. The original positions are calibrated to the zero for each consecutive set of data. Compared to the results from the analytical mapping, the deviation between subjects and directions are obviously reduced with the ICA mapping in the DoFs of rotations ϕ and θ (Fig. 8). There are similar performance for translations using both methods as these foot motions already yield a good performance (small error and deviation).

B. Experiment 2: Teleoperation

1) *Result of task 1:* While the trials carried out with the ICA were successful for all subjects, using the kinematics method lead to some failed trials. The kinematics method yielded 100%, 20%, 50%, 50% success rate for the four subjects. Fig. 9a shows that with the ICA mapping the subjects carry out more reproducible trials compared with the kinematic mapping, suggesting that they need less exploration to generate desired commands. The path deviation between consecutive trials using both methods are calculated using dynamic time warping. Fig. 9b plots the normalized path deviation using ICA and kinematics. The subjects yield 11.3% less deviation between consecutive trials using ICA.

2) *Result of task 2:* As shown in Figs. 10a,b, the subjects control speed during the movement. The subjects use $37.7\% \pm 1.6\%$ time on high and middle speed moving to the the area near the target and spent around $34.1\% \pm 2.8\%$ on slower speed to conduct fine positioning to adjust and press the button. Furthermore, we see in Fig. 10c that movement often combines two dimensions and the proportion of time with such combinations increases over the trials. Note that this happens while the time to complete the task decreases i.e. the movements' combination is not at the cost of slower motion control (Fig. 10d). This confirms the results of the first task

by showing that the subjects had no difficulty in combining directions using the novel interface.

3) *Subjective assessment:* The results of the first questionnaire indicate the raw rating of the factors, while the second one reflect the weights of each factor contributing to the workload. The results of these two questionnaires are shown in Fig. 11, including the factor contribution estimation (given in width of each column) and rating of these factors to the workload for the four subjects.

Results for the four subjects exhibit an average raw rating for mental and physical demands with 42.5 ± 15.2 and 53.7 ± 13.1 respectively, which are in the middle levels. The temporal demand is relatively low (31.2 ± 7.5) and the effort's rating is high (67.5 ± 10.5) as the tasks require accurate positioning. The assessments on performance and frustration are diverse between subjects with 42.5 ± 19.4 and 48.7 ± 24.9 respectively. The average overall workload computed as weighted rating is 46.7 ± 9.4 in average over the four subjects, which indicates that using the proposed foot interface to control a robotic arm is not too difficult and does not require much mental, physical effort (compare e.g. with MetaArm [18]).

The importance of each factor was also evaluated by the subjects. The mental demand shows one of the lowest weight as $10.6\% \pm 7.8\%$, indicating that the foot operation with the proposed interface requires relatively low mental effort for motion planning. $20.4\% \pm 8.3\%$ and $22.1\% \pm 10.1\%$ of the overall workload are indicated for the physical demand and effort, which is logical as the task designed required accurate operation with physical motion and attention. The performance and frustration contributions to the overall workload of $17.7\% \pm 5.0\%$ and $13.6\% \pm 9.8\%$ indicate that operating the robot with the foot interface does not stress the subjects.

C. Discussion

The characteristics of foot motions are different depending on the direction and subject. Especially, the deviation is large between subjects but small in the trials of each single subject. This motivated us to develop a data-driven approach to generate a subject-specific motion mapping for each user. Compared to analytical methods, the subject-specific mapping has effectively reduced the deviation between subjects and directions. The teleoperation test further verified the mapping method and motion control of the proposed system. The subjects can control a remote robot in four-DoF motion without difficulty using the novel foot interface.

Compared to existing foot interfaces for robotic surgery [24]–[27], [30], the interface presented in this paper provides a natural motion mapping from the foot to the robot. This enables users to continuously adjust the movement directions and flexibly vary its speeds. While button interfaces [24]–[26] require moving the whole leg, the dedicated sensing modules of the proposed foot interface provides users with a large force range while requiring only small movements and providing a resting place with automatic homing. This minimises fatigue and facilitates efficient foot positioning without requiring any visual check of the foot (especially useful for novice

Fig. 9. Accurate tracking of the wire of Fig. 6c carried out with the ICA and Kinematics. (a) The trajectories in each method in two consecutive trials of a typical subject. (b) The path deviation between consecutive trials.

Fig. 10. Using the novel foot interface to teleoperate accurate reaching. (a) Positions and velocity profile of the robot controlled by a typical subject. (b) Proportion of time at different speed levels over the four subjects. (c) Proportion of time with simultaneous movement in at least two dimensions for the four subjects. (d) Average completion time of first and last two trials.

Fig. 11. Subjects' NASA Task Load Index rating and weight.

users). Finally, the novel calibration using ICA considers the individual differences and provides a subject-specific mapping.

VII. CONCLUSION

While the feet exhibit well-controlled multi-DoF movements, most current foot interfaces for robot-aided surgery use a simple range of buttons or switches to command the robot at constant speed and one DoF at a time. Using such interfaces also require the operator to move the whole leg (which can be tiring during long operations) and to plan the combination and sequence of the buttons without haptic feedback [37]. The proposed foot-controlled interface has the following salient features:

- The interface was built to be comfortably controlled by natural foot movements, as shown in Fig. 1.
- The weight of the foot is supported by a ground support to save effort. The resulted friction was minimised using bearings and redundant joints.
- The module made of a spring and a force sensor mounted in series provides rich position and force feedback to assist foot positioning and closed loop control, requiring only small foot movements without limiting the applied force range and end-effector's motion range.

- A ICA-based data-driven approach was developed to provide an intuitive mapping for subject-specific motion patterns. This is due to the fact that subjects had substantially different movement patterns.

Validation experiments demonstrated these properties. The novel four-DoF passive interface may help unleashing the manipulation opportunities offered by foot control, in particular, in combination with the hands.

ACKNOWLEDGMENT

The authors thank Jonathan Eden for his suggestions on revising this manuscript; the subjects are also acknowledged for their participation in the tests.

REFERENCES

- [1] B. Hannaford, J. Rosen, D. W. Friedman, H. King, P. Roan, L. Cheng, D. Glozman, J. Ma, S. N. Kosari, and L. White, "Raven-ii: An open platform for surgical robotics research," *IEEE Transactions on Biomedical Engineering*, vol. 60, pp. 954–959, 2013.
- [2] A. Tobergte, P. Helmer, U. Hagn, P. Rouiller, S. Thielmann, S. Grange, A. Albu-Schaffer, F. Conti, and G. Hirzinger, "The sigma.7 haptic interface for mirosurge: A new bi-manual surgical console," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2011, pp. 3023–3030.
- [3] J. C. Bodner, H. F. Wykypiel, G. J. Wetscher, and T. M. Schmid, "First experiences with the da vinci operating robot in thoracic surgery," *European Journal of Cardio-thoracic Surgery*, vol. 25, pp. 844–851, 2004.
- [4] L. Cao, X. Li, P. T. Phan, A. M. H. Tiong, J. Liu, and S. J. Phee, "A novel robotic suturing system for flexible endoscopic surgery," in *IEEE International Conference on Robotics and Automation*, 2019, pp. 1514–1520.
- [5] L. Cao, X. Li, P. T. Phan, H. L. Kaan, J. Liu, W. Lai, Y. Huang, L. H. Minh, M. Miyasaka, K. Y. Ho, P. W. Y. Chiu, and S. J. Phee, "Sewing up the wounds: A robotic suturing system for flexible endoscopy," *IEEE Robotics & Automation Magazine*, 2019.
- [6] M. Nurok, T. M. Sundt, and A. Frankel, "Teamwork and communication in the operating room: Relationship to discrete outcomes and research challenges," *Anesthesiology Clinics*, vol. 29, pp. 1–11, 2011.
- [7] M. Turk, "Multimodal interaction: A review," *Pattern Recognition Letters*, vol. 36, pp. 189–195, 2014.
- [8] S. S. Kommu, P. Rimington, C. Anderson, and A. Rané, "Initial experience with the endoassist camera-holding robot in laparoscopic urological surgery," *Journal of Robotic Surgery*, vol. 1, pp. 133–137, 2007.
- [9] G. Yulun Wang and S. N. Darrin Uecker, "Speech interface for an automated endoscopic system," 2002, US Patent 6463361 B1.
- [10] R. Polet and J. Donnez, "Using a laparoscope manipulator (LAPMAN) in laparoscopic gynecological surgery," *Surgical Technology International*, vol. 17, pp. 187–191, 2008.

- [11] P. E. B. D. Y. Wang, R. U. S. A. Data and S. Taylor, "Automated endoscope system for optimal positioning," 1996, US Patent 5515478.
- [12] A. L. Simeone, E. Velloso, J. Alexander, and H. Gellersen, "Feet movement in desktop 3d interaction," in *IEEE Symposium on 3D User Interfaces*, 2014, pp. 71–74.
- [13] E. Abdi, E. Burdet, M. Bouri, S. Himidan, and H. Bleuler, "In a demanding task, three-handed manipulation is preferred to two-handed manipulation," *Scientific Reports*, vol. 6, p. 21758, 2016.
- [14] E. Abdi, E. Burdet, M. Bouri, and H. Bleuler, "Control of a supernumerary robotic hand by foot: An experimental study in virtual reality," *PLoS ONE*, vol. 10, p. e0134501, 2015.
- [15] D. W. Podbielski, J. Noble, H. S. Gill, M. Sit, and W.-C. Lam, "A comparison of hand- and foot-activated surgical tools in simulated ophthalmic surgery," *Canadian Journal of Ophthalmology*, vol. 47, pp. 414–417, 2012.
- [16] B. Hatscher and C. Hansen, "Hand, foot or voice: Alternative input modalities for touchless interaction in the medical domain," in *ACM International Conference on Multimodal Interaction*, 2018, pp. 145–153.
- [17] E. Velloso, D. Schmidt, J. Alexander, H. Gellersen, and A. Bulling, "The feet in human-computer interaction: A survey of foot-based interaction," *ACM Computing Surveys*, vol. 48, pp. 1–35, 2015.
- [18] M. Y. Saraiji, T. Sasaki, K. Kunze, K. Minamizawa, and M. Inami, "Metaarms: Body remapping using feet-controlled artificial arms," in *ACM Symposium on User Interface Software and Technology*, 2018, pp. 65–74.
- [19] M. C. Carrozza, A. Persichetti, C. Laschi, F. Vecchi, R. Lazzarini, P. Vacalebri, and P. Dario, "A wearable biomechatronic interface for controlling robots with voluntary foot movements," *IEEE/ASME Transactions on Mechatronics*, vol. 12, pp. 1–11, 2007.
- [20] K. Fukahori, D. Sakamoto, and T. Igarashi, "Exploring subtle foot plantar-based gestures with sock-placed pressure sensors," in *ACM Conference on Human Factors in Computing Systems*, 2015, pp. 3019–3028.
- [21] T. Kim, H. Ju, and J. R. Cooperstock, "Pressure or movement? usability of multi-functional foot-based interfaces," in *Designing Interactive Systems Conference*, 2018, pp. 1219–1227.
- [22] E. Velloso, J. Alexander, A. Bulling, and H. Gellersen, "Interactions under the desk: A characterisation of foot movements for input in a seated position," in *Human-Computer Interaction*, 2015, pp. 384–401.
- [23] K. Zhong, F. Tian, and H. Wang, "Foot menu: Using heel rotation information for menu selection," in *International Symposium on Wearable Computers*, 2011, pp. 115–116.
- [24] J. M. Sackier and Y. Wang, "Robotically assisted laparoscopic surgery," *Surgical Endoscopy*, vol. 8, pp. 63–66, 1994.
- [25] S. Voros, G.-P. Haber, J.-F. Menuet, J.-A. Long, and P. Cinquin, "ViKY robotic scope holder: Initial clinical experience and preliminary results using instrument tracking," *IEEE/ASME Transactions on Mechatronics*, vol. 15, pp. 879–886, 2010.
- [26] A. Mirbagheri, F. Farahmand, B. Ghannadi, K. Amini, S. Porsa, J. Shamsollahi, F. Karimian, K. Toulabi, and M. Owlia, "Operation and human clinical trials of robolens: an assistant robot for laparoscopic surgery," *Frontiers in Biomedical Technologies*, vol. 2, pp. 172–178, 2015.
- [27] E. Abdi, "Supernumerary robotic arm for three-handed surgical application: Behavioral study and design of human-machine interface," Ph.D. dissertation, Federal Institute of Technology Lausanne, 2017.
- [28] Y. Eguchi, H. Kadone, and K. Suzuki, "Standing mobility device with passive lower limb exoskeleton for upright locomotion," *IEEE/ASME Transactions on Mechatronics*, vol. 23, pp. 1608–1618, 2018.
- [29] E. Burdet, M. A. V. Mace, J.-L. Liardon, P. Bentley, and P. Rinne, "A force measurement mechanism," 2016, US Patent 3247986A1.
- [30] http://www.hiwin.tw/products/me/mtg_h100.aspxpa, accessed April 4, 2018.
- [31] L. van den Bedem, R. Hendrix, N. Rosielle, M. Steinbuch, and H. Nijmeijer, "Design of a minimally invasive surgical teleoperated master-slave system with haptic feedback," in *International Conference on Mechatronics and Automation*, 2009, pp. 60–65.
- [32] L. Cao, A. T. Dolovich, A. Chen, and W. C. Zhang, "Topology optimization of efficient and strong hybrid compliant mechanisms using a mixed mesh of beams and flexure hinges with strength control," *Mechanism and Machine Theory*, vol. 121, pp. 213–227, 2018.
- [33] L. Cao, A. T. Dolovich, A. L. Schwab, J. L. Herder, and W. C. Zhang, "Toward a unified design approach for both compliant mechanisms and rigid-body mechanisms: Module optimization," *Journal of Mechanical Design*, vol. 137, p. 122301, 2015.
- [34] L. Cao, A. T. Dolovich, and W. C. Zhang, "Hybrid compliant mechanism design using a mixed mesh of flexure hinge elements and beam elements

through topology optimization," *Journal of Mechanical Design*, vol. 137, p. 092303, 2015.

- [35] A. Hyvärinen and E. Oja, "Independent component analysis: algorithms and applications," *Neural Networks*, vol. 13, pp. 411–430, 2000.
- [36] S. G. Hart, "Nasa-task load index (nasa-tlx); 20 years later," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 50, pp. 904–908, 2006.
- [37] Y. Huang, E. Burdet, L. Cao, P. T. Phan, A. M. H. Tiong, P. Zheng, and S. J. Phee, "Performance evaluation of a foot interface to operate a robot arm," *IEEE Robotics and Automation Letters*, vol. 4, pp. 3302–3309, 2019.

Huang Yanpei received her M.Sc. degree in Manufacturing Systems and Engineering from Nanyang Technological University, Singapore, in 2016. She is currently pursuing her Ph.D study at Nanyang Technological University, Singapore. Her current research interests include human-machine interaction and medical robotics.

Etienne Burdet received the M.S. degree in mathematics, the M.S. degree in physics, and the Ph.D. degree in robotics, all from ETH-Zurich, Zurich, Switzerland, in 1990, 1991 and 1996, respectively. He is Professor at Imperial College of Science, Technology and Medicine in London, UK. He is doing research at the interface of robotics and bio-engineering.

Lin Cao received his Ph.D. degree in Mechanical Engineering from University of Saskatchewan, Canada, in 2015. He is a Research Fellow at Nanyang Technological University, Singapore. His research interests include flexible endoscopic surgical robots and soft robotics.

Phuoc Thien Phan received the B.Eng. degree in Mechanical Engineering from Vietnam National University, Ho Chi Minh city University of Technology in 2015. He is with Graduate School of Biomedical Engineering, University of New South Wales, Sydney, Australia. His research interests include the mechanical design of medical devices.

Anthony Meng Huat Tiong received the M.Eng from Imperial College London, UK in 2015. He is currently a Research Associate at Nanyang Technological University, Singapore. His research interests include deep learning and data analytics.

Soo Jay Phee received the B.Eng and M.Eng degrees from Nanyang Technological University, Singapore in 1996 and 1999 respectively. He obtained his Ph.D. from Scuola Superiore Sant'Anna, Pisa, Italy in 2002. He is Professor at Nanyang Technological University, Singapore. His research interests include medical robotics and mechatronics in medicine.