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Hand-impedance measurements with robots during laparoscopy training☆

Harun Tugal [a,b,*], Benjamin Gautier [a,b], Benjie Tang [c], Ghulam Nabi [c], Mustafa Suphi Erden [a,b]

[a] Sensors, Signals and Systems, School of Engineering and Physical Sciences, Heriot-Watt University, EH14 4AL, UK
[b] Edinburgh Centre for Robotics, Edinburgh, UK
[c] Cuschieri Skills Centre, Ninewells Hospital and Medical School, University of Dundee, DD1 9SY, Dundee, UK

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ABSTRACT

This paper presents hand-impedance measurements during laparoscopic training with physically interactive manipulators. We develop a co-manipulated robotic system allowing hand-impedance measurements in an active manipulation task with occasional environmental contact. Six professional, four trainee surgeons, and ten novice subjects participated in our experimental program for a suturing activity where the novice subjects were involved in a five weeks training practice. Variable admittance controlled robots, attached to the tools with force sensors, applied step vice velocity disturbances while subjects were trying to set the needle perpendicular to the surgical driver. Hereby, impedances of the left and right hands were computed in four different directions. Then, the measured impedance parameters across all subjects were compared with respect to the participants' level of proficiency and skill progression via statistical analyses to demonstrate effectiveness of the system. Results indicate that hand-impedance in the direction of the suturing-line demonstrates a consistent change throughout training and across different levels of expertise in laparoscopy. Therefore, hand-impedance information, proposed here, can pave the way for future development of robotic assessment or assistance in laparoscopy training programs.

1. Introduction

Minimally Invasive Surgery (MIS) methods are aimed at reducing the damage to the body tissues during diagnostic or surgical procedures, which connotes less post-operative pain, lower risk of infection, and a quicker recovery time for the patients as compared to conventional (open) surgery [1]. Laparoscopy is minimally-invasive inspection and surgery inside the abdominal cavity; surgeon can access inside of the abdomen or pelvis with minimal surgical wounds by using laparoscopic instruments such as small-scale tubes and cameras (known as endoscope). Improvements within the scaled-down display devices and special surgical instruments have given rise to the utilization of this technique. Consequently, laparoscopy has become the main method for surgical procedures around the abdominal region such as cholecystectomy and appendectomy surgeries [2,3]. In a more advanced robotic system surgeons operate robots from a console based on the 3D image via two master controllers in this way robots can enhance motion precision (e.g., via suppression hand vibrations). The focus of this paper is laparoscopy (manual) training, and not robotic surgery [4]; thus, robots are used for the purposes of hand-impedance measurement in laparoscopy performance.

Laparoscopic technique also brings additional challenges to the surgeons: operations are difficult to learn and perform. The primary challenges in laparoscopic procedures include the disturbed observation through a non-stationary camera platform and the loss of depth perception as the operation is viewed on a two-dimensional flat screen [4,5]. Besides, manipulation is non-intuitive due to the discrepancy between the hand movements and tip of the laparoscopic tools; the well known fulcrum effect. The usage of these tools also leads to the loss of tactile sensing [6]. To cope with these difficulties surgeons are required to carry out an extensive training program, where with limited one-to-one expert guidance trainees try to learn from their own mistakes or through the feedback of virtual trainers based on the count of some task related performance measures [7,8].

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* Corresponding author at: Sensors, Signals and Systems, School of Engineering and Physical Sciences, Heriot-Watt University, EH14 4AL, UK.
E-mail addresses: h.tugal@hw.ac.uk (H. Tugal), bg32@hw.ac.uk (B. Gautier), b.tang@dundee.ac.uk (B. Tang), g.nabi@dundee.ac.uk (G. Nabi), m.s.erden@hw.ac.uk (M.S. Erden).

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In laparoscopy training, coaching has been proven to have significant influence on the learning curve, thereby structured coaching not only with expert surgeons but also with assistive robots might present a key element in the acquisition of the laparoscopic surgical skills [9,10]. Hand impedance-measurements can potentially be used for both assessment and training purposes for laparoscopy. The current paper focuses on the assessment aspect, by making measurements and using them to distinguish between novice and professional performances. However the impedance-measurements have the potential to be used to provide feedback on their hand-impedance characteristics and to inform them how to change the use of hand/body [11] to bring the hand-impedance to an optimal, similar to what expert coaches do. The current paper presents a first study to measure hand-impedance in laparoscopy activity, and therefore is a first step towards exploring the promises of such measure which constitutes a biomechanical measure of performance. Currently, the assessment techniques for laparoscopy mostly focus on the kinematic movement of the tools/surgeons' upper limps (short distance, time, frequency content, etc.) [12], [13,14]. There is no criterion to our knowledge that monitors the state of human biomechanics, such as hand-impedance or muscle activity, and no objective assessment method that monitors directly the biomechanical behaviour of the trainee. A biomechanical measure of performance might provide an objective assessment, difficult, if not impossible, to trick. Our study, in this sense, provides a novel measure with a totally new characteristics, a measure of biomechanical behaviour, inspired by our previous work on manual welding [15,16].

In this paper, whose preliminary findings involving only novice subjects with a short period of time training were presented in [17], hand-impedances of six professional and four trainee surgeons along with ten novice subjects, who participated in a five weeks laparoscopy training program, were measured during laparoscopy suturing experiments. Measurements were performed while participants were trying to set the needle with respect to the needle driver for preparation to enter the suturing pad. Small step-vice velocity disturbances were applied with the robotic manipulators while participants were manipulating the needle. Various impedance parameters measured in different directions at different periods within the program and statistical analyses were carried out to identify any significant difference between the expertise levels.

2. Related work

The musculoskeletal system forming the human hand along with the arm can be associated or assumed to behave, all together, as a mechanical system. Dynamical characteristics of this system, in general, is described as a mechanical impedance while excluding the voluntary conducts [18]. This impedance characteristic is encountered frequently within the human–robot interaction such that any slight vibration or oscillation at the point of touch involuntary extinguishes with a human hand grip [19]. In addition to this passive behaviour, human hand reaction to external disturbances is modelled locally as a Linear Time Invariant (LTI) system consisting of a mass, spring, and damper [20].

Based on such modelling, measuring human hand-impedance or arm joint impedances implies estimation of the mass, spring, and damping parameters within the aforementioned LTI model. Applying small impulse type force or position perturbations from a grip point and analysing the resulting response behaviour of the hand, such as interaction force and displacement from the equilibrium posture, is extensively revisited methodology; for instance see [15,21] for the force and [22–24] for the position disturbances.

To apply perturbations and measure the hand position, admittance controlled robotic manipulators have been used in our previous studies [15,25] within the aforementioned techniques without considering the overall system's stability. This technique allows us to measure the hand-impedance, during actual and professional task execution, affected by the muscle activity levels and hand–arm orientations specific to the professional task. In this way, hand-impedance measurements can be applied to real-life problems [16], rather than only to the laboratory devised experimental manipulation and only for passive (inactive) arm impedance measurements. But, unlike in applications such as manual welding [15] or airbrush painting [25], the training for suturing requires frequent contact of the laparoscopy instrument with hard (key hole, the needle and tip of the other instrument) and soft (the pad to be sutured) structures. Thus, special care must be taken to eliminate the instability that might occur due to such contacts during the training and measurement procedures.

To assess the stability of an interactive robotic architecture, passivity, a sufficient condition for the stability, is the main technique applied by many researchers. This method provides an elegant tool to eliminate severe constraints caused by the unmodelled dynamics of the robotic systems by considering only the input and output energy [26]. But, a major problem with this method is that the overall design becomes too conservative. To reduce the conservatism, one can design passivity observer/controller [27], by using measured forces and velocities to estimate the total power or the energy injected to the system. Yet, integrated energy during passive motion is the inherent limitation of this method; that phenomenon prevents instant active behaviour detection in real time implementation and requires intuitive energy resetting methodology [28,29].

Recently, attention has also been focused on deriving empirical instability detection methodology by analysing forces or motions of the robot in the frequency domain. This procedure is intuitively stating that a stable motion does not exhibit unintentional high frequency movements or vibrations. By distinguishing the desired motions from the undesired ones via haptic stability observer (HSO) [30], unwanted actions can be eliminated via penalization techniques such as an increase in the overall impedance of the system by appropriate control action [30–32]. Here, following [30,32], we implemented an adaptive admittance control that allows both transparent co-manipulation in normal manipulation conditions and low admittance in case of oscillations during contact.

Accordingly, we developed a robotic measurement system for hand-impedance measurements in an active manipulation task with occasional environmental contact, implementing the system to the case of laparoscopy training exercises. Measured parameters, here, are comparable to and in the same order as in previous hand-impedance measurements (see, e.g., [15]). Statistically significant difference was observed in some parameters across the surgeons, also before and after training of the novice subjects and plausible implication of this was proposed. This observation would support the idea that impedance measurements relate to laparoscopic manipulation skills that are gained through training and experience.

3. Methods

3.1. Experimental setup

The experimental setup consisted of an MIS training box, 2 Universal Robots (UR3), and 2 ATI Gamma force/torque (FT) sensors (with ATI FT 9105-NETB sensor box). The FT sensors were inserted between a special mechanical adapter which was integrated to the MIS tool and the robot's end-effector, see Fig. 1.

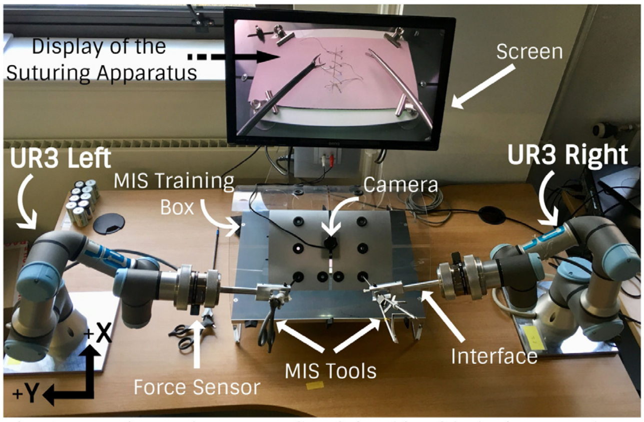

Fig. 1. Experimental setup: MIS training kit with the integrated two UR3 robots.

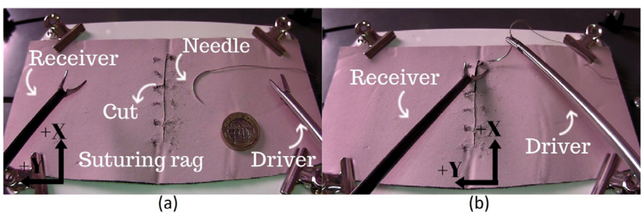

Fig. 2. (a) The suturing-training rag, the needle, and tips of the MIS tools. (b) Desired needle and tools position for a skin entrance.

The UR3 robots are lightweight, have six degrees of freedom, capable of carrying 3 kg at their end effectors, and controlled by their own control boxes providing 125 Hz control cycle. To create a human–robot interaction, an admittance control architecture with variable parameters was implemented by using the Robot Operation System (ROS) and the FT sensors' measurements with a sampling frequency (f_s) equivalent to the robot's control cycle ($f_s = 125$ Hz).

3.2. Experimental procedure: Setting of the needle

Needle setting was chosen as a target task because setting the needle perpendicular to the bar of the needle driver is one of the most difficult steps and perhaps the most crucial step in an effective laparoscopic suturing. While the subjects were setting the needle robotic manipulators connected to the two MIS tools, the receiver (left hand tool) and the driver (right hand tool), passively followed the hand movements and they became active from time to time to introduce slight disturbances for the measurements.

In this study we followed the needle setting instructions and procedure as described in [33]. The experiment starts by placing the needle at the right half side of the suturing rag as illustrated in Fig. 2(a). The participants were instructed to set the needle as shown in Fig. 2(b). The subjects were advised to hold the front section of the needle with the receiver and back section of the needle with the driver, thus the unnecessary steps were eliminated to reduce the task completion time, which would eventually reduce the effect of the fatigue, see Fig. 3(a) for the graphical illustration of the mentioned needle segregation. Additionally, in order to clarify the step-wise "needle dancing" technique (i.e. positioning the needle and orienting the angle), the needle was hypothetically divided into three sections as illustrated in Fig. 3(b).

Then, the subjects were instructed to follow the subsequent steps to set the needle;

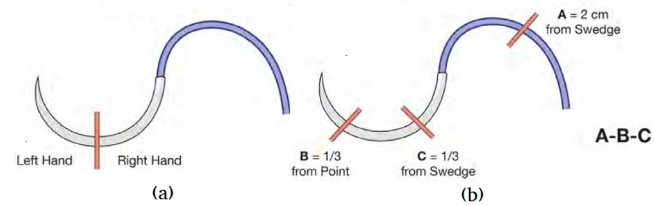

Fig. 3. (a) The front section of the needle should only be grasped with left hand tool and in a similar manner the back section of the needle needs to be grasped with right hand tool. (b) Segregation of the needle for guidance purposes [33].

- **A→Drag:** The driver starts at position 'A', see Fig. 3(b). Then, passes the needle to receiver which will hold the needle at position 'B'.
- **B→Right:** The needle is righted to correct the position by pulling/pushing the driver from point 'A' and rotating the receiver from point 'B'. Once the needle is at the right angle the driver is released from point 'A'.
- **C→Confirm:** The needle is now grasped by driver at point 'C' and locked. The orientation is tested with an axial rotation of the driver. If the angle is not appropriate for entering the skin, then the process is repeated in the reverse order.

We refer the reader to [33] for more detailed information and for other advanced needle setting techniques.

Before the experiments, the participants were introduced to the MIS training kit and usage of the MIS tools, they then were instructed about the process of suturing. The overall experimental protocol was as follows;

(1) Participant grasped the handles. The needle was initially stationary on the pad as in Fig. 2(a),
(2) Participant picked the needle's strand with the driver (first part of the step **A**),
(3) Participant passed the needle to the receiver (second part of the step **A**),
(4) Participant corrected orientation of the needle (step **B**),
(5) Participant re-grasped the needle with the driver at the correct location and tested the orientation (step **C**),
(6) Participant repeated steps 3–5 until a successful grasp/orientation by the driver was achieved,
(7) Participant repeated steps 1–6 within an experimental session (max 25 min).

For the novice participants, a demonstration of a complete suturing with and without robots were performed by the authors to demonstrate these in practice.

3.3. Empirical instability disclosure

Stability is inherently the main concern while designing a control architecture for a robotic system interacting with its environment. Therefore, there has been a great deal of effort to design absolutely stable interactive robotic systems whose application areas vary from industrial and military to bilateral teleoperation [34–37].

Inspired from [30,32], a variable admittance controller was designed by using the HSO index, I_p, and a recursive stability index, I_f. Those indices can be determined by analysing the robot's velocities/positions or interaction forces in frequency domain via using FFT. A ratio, known as HSO, is obtained by dividing the sum of the amplitudes of unstable frequency components with the sum of the amplitudes of all frequency components. The changes

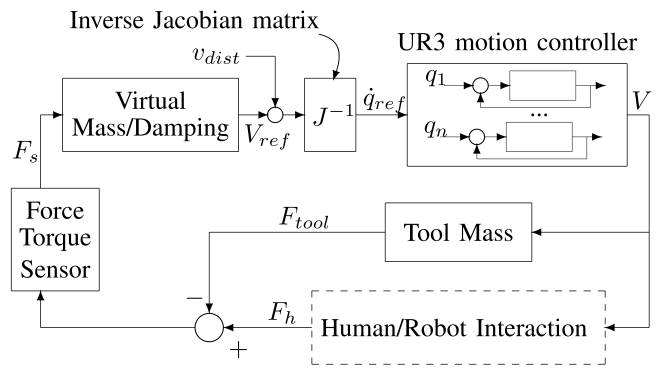

Fig. 4. Block diagram of the intendant Human–Robot interaction with implemented admittance control architecture. Explicit velocity perturbations (v_{dist}) are introduced for hand-impedance measurements.

in this parameter can be used as a remark to detect the overall instability (or stability).

$$I_p[kf_s] = \frac{\sum_{f=f_c}^{f_s/2} |P_f(f)|}{\sum_{f=f_0}^{f_s/2} |P_f(f)|},$$

where $P_f(f)$ of the frequency components f can be calculated via FFT of the determined signal (e.g., force) and f_0 denotes the lowest frequency within the FFT. Another, more commonly applied, recursive stability index is given as

$$I_f[kf_s] = I_p[kf_s]I_{frms}[kf_s] + \lambda I_f[(k-1)f_s],$$

where I_{frms} is the ratio between the root mean square and the maximum value of the measured force signal and λ is a tunable time constant of the index [32]. Ultimately, one can enhance system's robustness by associating increase of I_f to an overall impedance increment in the virtual end-effector dynamics of the admittance controlled system to empirically provide stability.

3.4. Implemented admittance control architecture

The admittance control architecture's block diagram is given in Fig. 4. The force sensor at the robot's end effector measures the interaction force with the tool kit and based on this measurement the controller generates desired velocities. In Cartesian space, the motion dynamics of the admittance controller can be described as

$$F_s = M_a\dot{V}_{ref} + D_aV_{ref}, \tag{1}$$

where $F_s, V_{ref} \in \mathbb{R}^6$ denote the measured interaction force/torque and desired end effector velocity vectors. The diagonal matrices $M_a, D_a \in \mathbb{R}^{6\times6}$ are controller's virtual mass and damping, respectively. The desired velocities in Cartesian space, given in (1) and computed based on the interaction force/torque along with the virtual mass and damping, can be transformed into the joint space by using the robot's Jacobian matrix $J(q) \in \mathbb{R}^{6\times6}$. One can determine the desired robot joints' velocities, $\dot{q}_{ref} \in \mathbb{R}^6$, while assuming that the inverse of the Jacobian matrix exists (robot is not operating nearby the singular joint configuration) as

$$\dot{q}_{ref} = J^{-1}(q)V_{ref}.$$

Admittance control parameters, M_a and D_a, need to be meticulously determined due to the inherent trade off between the stability and transparency of the robot while following the human hands' movements [38]. Here, the controller's parameters, mass and damping, were designed to be variable parameters and their alteration was associated with the stability indices as

$$D_a = D_u + D_uI_f, \quad M_a = \frac{m_{min}}{d_{min}}D_a, \tag{2}$$

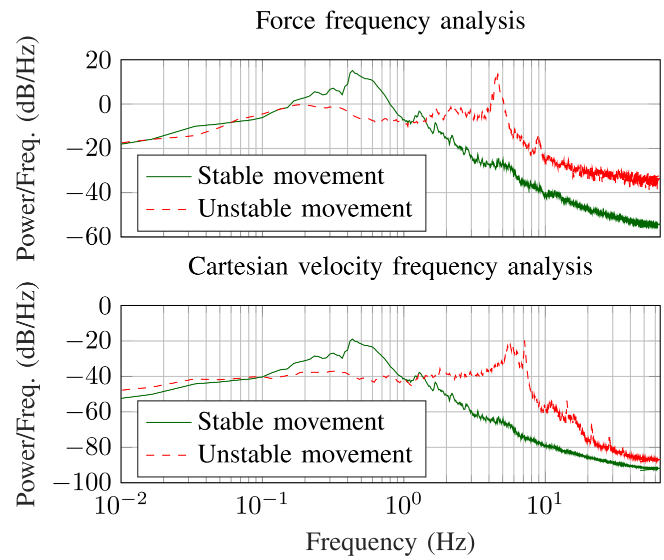

Fig. 5. Power spectral densities of the force (above) and velocity (below) measurements during experimental laparoscopy by using FFT.

where m_{min} and d_{min} are minimum virtual mass and damping parameters such that stable free space movement is maintained, $I \in \mathbb{R}^{6\times6}$ denotes the identity matrix, and $D_u \in \mathbb{R}^{6\times6}$ is used to express the dimensionless quantity I_f in physical units and it was denoted as $D_u = d_{min}I$ N s/m. When an oscillation is detected the variable parameters, in (2), increase based on the increments in the stability index. Thus, the unwanted movements leading to the instable behaviour are suppressed by increasing the overall impedance of the robot end-effector.

3.5. Frequency analysis of the laparoscopic operation with robots

Dynamics of the intrinsic hand movement in daily use are significant over the low frequency range, 0–10 Hz [39]. Laparoscopic operations require gradual and dedicated hand motions; therefore one can expect to have significant frequency content during the operations in a much lower bandwidth than 0–10 Hz. To quantitatively determine principal frequencies during laparoscopy, initially, we carried out different experimental scenarios where laparoscopic tools were manipulated by the authors first in a gradual, stable manner and then in a fast and oscillatory manner, which can be characterized as an undesired, *instable* movement. The stable motions were achieved under high mass and damping parameters (m = 5–7 kg, d = 50–100 N s/m) within the designed admittance controller, similarly instability was obtained under low admittance control parameters (m = 0.5–2 kg, d = 5–30 N s/m). After running 6 different experimental scenarios for each of stable and unstable motions (12 in total), we have analysed the interaction forces and Cartesian space velocity measurements in frequency domain by using fast Fourier transform (FFT) [40]. The frequency spectrum of the both signals are illustrated in Fig. 5.

As seen from the frequency spectrum, the principal frequencies of the desired stable motions in both measures (force and velocity) are lower than 1 Hz. On the contrary undesired, instable, motions' principal frequencies are settled at frequencies higher than 2 Hz. In this regard, a finer frequency resolution, f_Δ, within the FFT analysis enables us to distinguish the principle frequencies of the desired and undesired motions. To obtain this, a large value of FFT window size, N, with respect to determined sampling frequency, needs to be chosen, as $f_\Delta = \frac{f_s}{N}$. Based on

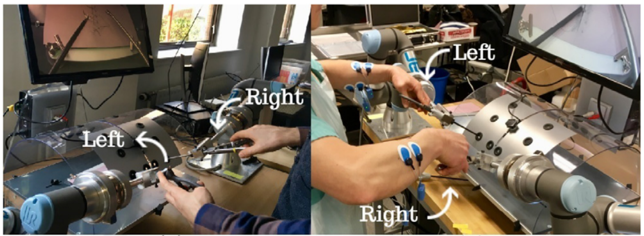

Fig. 6. A novice participant (a) and a professional surgeon (b) operating the tools within the experiments.

this, we have used the frequency resolution $f_\Delta = 0.9766$ Hz, by choosing $N = 128$, and identified the critical frequency, f_c, as 1.9531 Hz in order to distinguish between stable movements and unstable–involuntary–oscillatory motions. In this way, any movements higher than the critical frequency were interpreted as an involuntary behaviour. Besides that, we chose to use the force signal (as in [32]) in the forthcoming frequency analyses as force becomes the dominant measure when the MIS tool is in contact with its environment, typically while suturing.

3.6. Subjects and impedance measurements

Six consultant surgeons (male), experienced in laparoscopy, and four trainee surgeons (male), experienced in traditional surgical procedure yet in a training program for laparoscopic operations, voluntarily participated the experiments in the Cuschieri Skills Centre at the University of Dundee. In average, the professional surgeons had 15 years' expertise in general surgical practice and 133 hours in laparoscopic operations, and the trainee surgeons had 5 years' surgical expertise and had gained 3 h laparoscopic training. Based on the test results of the Edinburgh Handedness Inventory [41], one of the professional and one of the trainee surgeons were left-handed and the rest were right-handed.

Additionally, ten novice subjects (5 males and 5 females) took part in a five weeks training program, where experiments and measurements of 6 h in total per participant took place in Week 1 (W1), Week 3 (W3), and Week 5 (W5). Week 2 and Week 4 were considered to be training only slots where trainees practised the exercises (4 h in total per participant) so no measurements were taken during these periods. All the novice subjects were recruited among the Ph.D. students of the Institute of Sensors, Signals, and Systems at Heriot-Watt University (HWU), on a voluntary basis. The novice subjects did not have any prior experience on laparoscopic operations and they used the MIS training kit for the first time during our experiments. All the novice participants considered themselves as right-handed, yet according to the Edinburgh Handedness Inventory two of them were actually mixed-handers. The experiment protocol was approved by the Ethics Committee of the HWU. All the participants were provided with an information sheet, and they gave their informed consent prior to the experiments.

The participants were instructed about how to set the needle, enter the skin with a needle, and tie two different surgical knots by using MIS tools. In the beginning, the subjects familiarized themselves with the MIS training system. They performed setting the needle process freely without the robots. After a couple of successful attempts, the subjects carried out the same process while adaptive admittance controlled robots with $m_{min} = 5$ kg and $d_{min} = 50$ N s/m were attached to the tools and passively followed the hand movement of the participants.

Table 1
System's parameters.

Frequency	Controller	Perturbation
$f_\Delta = 0.9766$ Hz	$m_{min} = 5$ kg	$\lvert v_{dist}(t)\rvert = 0.15$ m/s
$f_c = 1.9531$ Hz	$d_{min} = 50$ N s/m	$t_\Delta =$ 100-ms

During the measurement experiments, the subjects performed the needle setting process/task inclusive of the disturbances, as seen in Fig. 6. The subjects were informed in advance that the robots would apply perturbations. To prevent any voluntary actions against the disturbances, the perturbations were composed of 100-ms duration 0.15 m/s velocity impulses (v_{dist}) in one of the eight ($\pm v_n$, $\pm x$, $\pm y$, $\pm z$) directions, randomly applied without replacement as,

$$v_{dist}(t) = \begin{cases} 0, & t \le t_d, \\ 0.15\,\mathrm{m/s}, & t_d < t \le t_u, \end{cases}$$

where t_d denotes moment before the disturbance and $t_u - t_d =$ 100-ms [42]. Fig. 7 illustrates one of the implemented perturbations during the experiment. Here, v_n corresponds to the direction perpendicular to the moving plane of the tools (as explained in the subsequent paragraph), x corresponds to the direction that the subjects are faced and which is along the suturing line, y corresponds to the direction perpendicular to the subjects and the suturing line, and z corresponds to the direction parallel to the gravity, see the x and y directions illustrated in Fig. 1. The disturbances were introduced at random instances, making sure that there were at least 4 sec in between. Also to reduce the effects of the fatigue, particularly with the novice subjects, each experimental session lasted around 18–25 min [43,44]. The aforementioned system's parameters used within the experiments are given also in Table 1.

Making impedance measurements in a dynamically changing direction, v_n, besides the globally fixed Cartesian directions, was motivated by the idea that humans might be modulating the directional impedance according to the movement of the hand. To define a motion plane regarding to the action of the robot's end effector at the Cartesian space, three consecutive tool positions were chosen as $P_0 = (p_{x_0}, p_{y_0}, p_{z_0})$, $P_1 = (p_{x_1}, p_{y_1}, p_{z_1})$, and $P_2 = (p_{x_2}, p_{y_2}, p_{z_2})$ such that P_0 denotes the most recent position estimation attained via designed Kalman filter based on the dynamic model related to position (p_k) and velocity (v_k) as

$$\begin{bmatrix} \hat{p}_{k+1} \\ \hat{v}_{k+1} \end{bmatrix} = \begin{bmatrix} I & \Delta t \\ 0 & I - M_a^{-1} D_a \Delta t \end{bmatrix} \begin{bmatrix} \hat{p}_k \\ \hat{v}_k \end{bmatrix} + \begin{bmatrix} 0 \\ M_a^{-1} \Delta t \end{bmatrix} F_s,$$

where $\hat{p}$, $\hat{v}$, and Δt denote estimated position, estimated velocity, and the sampling time, respectively. The motion plane can be represented with two vectors $\overrightarrow{R_{10}} = (p_{x_0} - p_{x_1}, p_{y_0} - p_{y_1}, p_{z_0} - p_{z_1})$ and $\overrightarrow{R_{12}} = (p_{x_2} - p_{x_1}, p_{y_2} - p_{y_1}, p_{z_2} - p_{z_1})$ which are denoted by the tool's positions. Thereafter, the normal vector (v_n) can be determined by the cross-product of these two vectors ($\overrightarrow{R_{10}} \times \overrightarrow{R_{12}}$) which is inherently perpendicular to the motion plane defined by the end effector positions. A predefined amplitude can be associated to $|v_n|$ by normalizing the vector. A graphical illustration for this type of vector on the Cartesian plane is given in Fig. 8.

The use of ranking scales (knot security, symmetry of suture, position of suture, operative times, etc.), recording the penalties and mistakes made during the laparoscopic procedure is commonly used assessment technique [45]. Also, image processing or accelerometer data analysing techniques, which require additional effort to create algorithms, are applied to assess motion quality and smoothness during laparoscopic operations [46–48]. However, the methods reported are not yet standardized, availability is limited, and the process involves complex recording

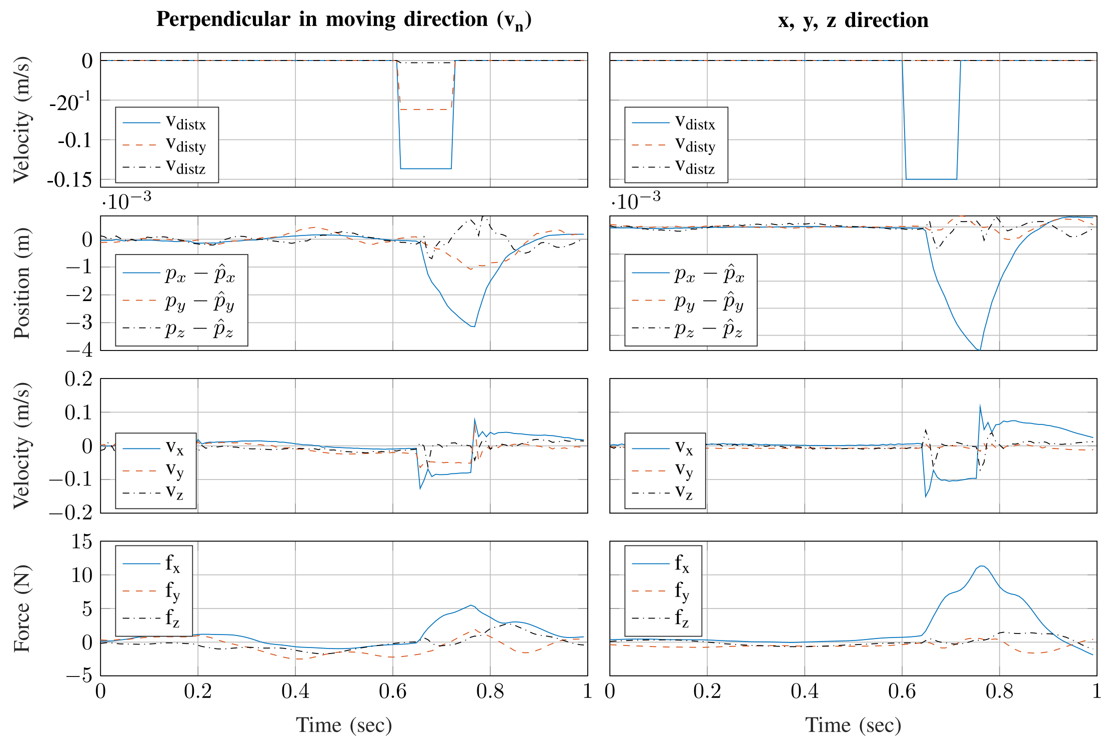

Fig. 7. Data collected from one of the experiments and exclusively zoomed into the disturbance period for the illustration and clarity. The left column shows when a disturbance was applied in (v_n) direction and right column shows when disturbance was applied in x, y, and z direction. Mismatches between the actual (p) and predicted ($\hat{p}$) positions are illustrated in the second row to indicate the effect of the perturbations. Third and the last rows illustrate the measured velocities and forces, respectively.

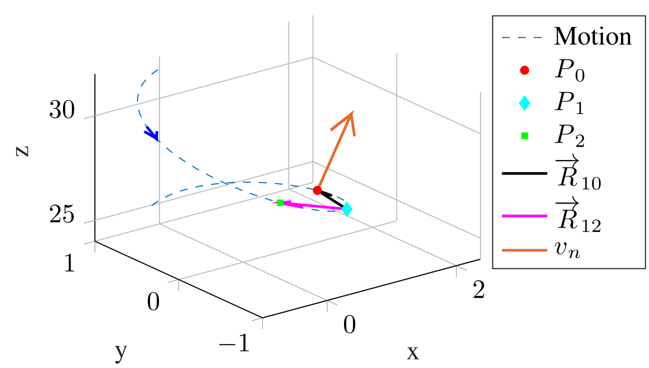

Fig. 8. A reproduction for $\overrightarrow{R}_{10}$, $\overrightarrow{R}_{12}$, and v_n vectors within the motion plane with a helical movement on the x, y, and z plane.

systems and image analysis [49]. To quantitatively illustrate the expertise level of the surgeons and progression of the novice subjects throughout the training program we have simply counted how many times they have completed the needle setting task (T) during the experiments. Number of the needle dropping (P) was used as a penalization criterion, thus any unnecessary movements extending duration of the tests were avoided by the participants during the experiments. Subsequently, an overall performance per minutes (opm) criterion was calculated by subtracting number of the penalties from the total number of the completed task ($T - P$) and dividing this with the time taken (min) by individual subjects during the experiments. In this way we constructed a practical and easy measure of performance for our purpose of assessing the specific exercise we employ, through capturing the three basic criteria; achievement, operation time, and the mistake of dropping the needle.

3.7. Hand impedance estimation

Human hand impedance was modelled as an LTI passive operator in each of the three main directions (x, y, z) and also perpendicular to the moving direction (v_n) as

$$\Delta f(t) = m_h \Delta\ddot{p}(t) + d_h \Delta\dot{p}(t) + k_h \Delta p(t), \tag{3}$$

where m_h, d_h, and k_h are the mass, damping, and stiffness parameters of the human hand contact impedance in Cartesian and v_n directions and Δp states the position of the hand in Cartesian space. We perform decoupled measurements as we apply single disturbance in one of these directions and measure the reaction in the same direction. By using measured/calculated data of force (Δf), position (Δp), velocity ($\Delta\dot{p}$), and acceleration[1] ($\Delta\ddot{p}$), the equality in (3) can be solved for estimating the impedance parameters by using the well-known ordinary least-squares method as

$$\begin{bmatrix} k_h & d_h & m_h \end{bmatrix}^\top = (X_{state}^\top X_{state})^{-1} X_{state}^\top \Delta f,$$

where $X_{state} = [\Delta p \quad \Delta\dot{p} \quad \Delta\ddot{p}]$ and $^\top$ means transpose.

In addition to that, we also estimated *rate-hardness* (rh) measures in each specified directions as proposed in [50], as a more intuitive measure of the human-hand resistance to external disturbances. The reader is referred to [15] for more detailed information about how to calculate the rh, Δf, and Δp values in Cartesian coordinate directions. Briefly, voluntary motion along the axis of perturbation is eliminated from our computation by subtracting the velocity and force at the instant just before the disturbance from the velocity and force recorded after the disturbance. In this way, only the velocity and force components that result from the disturbance are retained and the impedance

[1] Obtained numerically via implementing finite difference approximations to the filtered velocity measurements.

Table 2
Impedance measures in v_n, x, y, and z directions.

Left hand	**Week 1 (W1)** Impedances (Avg. ± Std. dev.)				Right hand	**Week 1 (W1)** Impedances (Avg. ± Std. dev.)			
	v_n	x	y	z		v_n	x	y	z
rh (N/m)	541 ± 597	437 ± 147	503 ± 210	362 ± 140	rh (N/m)	929 ± 846	706 ± 279	844 ± 313	815 ± 251
m_h (kg)	0.022 ± 0.023	0.023 ± 0.013	0.034 ± 0.015	0.017 ± 0.009	m_h (kg)	0.037 ± 0.03	0.051 ± 0.02	0.038 ± 0.02	0.038 ± 0.02
d_h (N s/m)	7.9 ± 6.4	6.7 ± 3.8	13 ± 5	4.9 ± 3.1	d_h (N s/m)	13.7 ± 7.6	17.4 ± 6.1	14.6 ± 7.5	11.6 ± 6.3
k_h (N/m)	357 ± 304	296 ± 144	286 ± 181	310 ± 143	k_h (N/m)	578 ± 366	359 ± 207	628 ± 318	564 ± 208
	Week 3 (W3) Impedances (Avg. ± Std. dev.)					**Week 3 (W3)** Impedances (Avg. ± Std. dev.)			
rh (N/m)	536 ± 660	440 ± 170	470 ± 211	326 ± 134	rh (N/m)	883 ± 521	735 ± 288	834 ± 282	839 ± 284
m_h (kg)	0.019 ± 0.016	0.026 ± 0.012	0.025 ± 0.012	0.015 ± 0.009	m_h (kg)	0.041 ± 0.03	0.044 ± 0.019	0.037 ± 0.018	0.039 ± 0.02
d_h (N s/m)	7.8 ± 5.9	8 ± 3.8	12.3 ± 4.4	4.3 ± 2.6	d_h (N s/m)	14.8 ± 8	15.4 ± 6.5	15.5 ± 6.5	10.9 ± 6.3
k_h (N/m)	367 ± 412	273 ± 160	297 ± 187	304 ± 132	k_h (N/m)	560 ± 337	422 ± 216	591 ± 268	600 ± 234
	Week 5 (W5) Impedances (Avg. ± Std. dev.)					**Week 5 (W5)** Impedances (Avg. ± Std. dev.)			
rh (N/m)	443 ± 249	463 ± 171	460 ± 204	342 ± 136	rh (N/m)	851 ± 490	713 ± 272	830 ± 324	805 ± 270
m_h (kg)	0.019 ± 0.013	0.029 ± 0.014	0.022 ± 0.012	0.017 ± 0.009	m_h (kg)	0.042 ± 0.03	0.044 ± 0.02	0.041 ± 0.019	0.038 ± 0.02
d_h (N s/m)	7.2 ± 3.8	8.2 ± 4.3	11.5 ± 4.6	4.1 ± 2.4	d_h (N s/m)	$15, 3 \pm 7.7$	14.9 ± 6	16.5 ± 6	10.4 ± 6.4
k_h (N/m)	320 ± 221	292 ± 183	289 ± 188	312 ± 142	k_h (N/m)	536 ± 344	424 ± 234	571 ± 315	582 ± 228
	Trne surgeons Impedances (Avg. ± Std. dev.)					**Trne surgeons** Impedances (Avg. ± Std. dev.)			
rh (N/m)	469 ± 288	468 ± 251	547 ± 314	298 ± 162	rh (N/m)	938 ± 558	771 ± 243	899 ± 378	736 ± 260
m_h (kg)	0.024 ± 0.01	0.023 ± 0.01	0.026 ± 0.01	0.019 ± 0.009	m_h (kg)	0.036 ± 0.03	0.027 ± 0.01	0.039 ± 0.02	0.039 ± 0.02
d_h (N s/m)	9.5 ± 4.9	7.5 ± 3.8	14.4 ± 5.7	5 ± 2.6	d_h (N s/m)	13.4 ± 7.3	9.1 ± 4.4	19.7 ± 7.9	12.2 ± 6.8
k_h (N/m)	318 ± 272	300 ± 170	276 ± 223	264 ± 158	k_h (N/m)	641 ± 477	553 ± 241	586 ± 386	493 ± 233
	Pro surgeons Impedances (Avg. ± Std. dev.)					**Pro surgeons** Impedances (Avg. ± Std. dev.)			
rh (N/m)	487 ± 247	690 ± 291	568 ± 285	400 ± 215	rh (N/m)	1002 ± 568	797 ± 277	883 ± 337	730 ± 297
m_h (kg)	0.021 ± 0.015	0.039 ± 0.021	0.027 ± 0.017	0.018 ± 0.012	m_h (kg)	0.045 ± 0.04	0.032 ± 0.01	0.038 ± 0.02	0.036 ± 0.018
d_h (N s/m)	8.2 ± 4.3	12.6 ± 6.4	13.9 ± 5.2	5.1 ± 3.4	d_h (N s/m)	14.7 ± 9.4	10.7 ± 5.5	18.1 ± 7	10.8 ± 5.3
k_h (N/m)	355 ± 255	378 ± 246	347 ± 286	345 ± 204	k_h (N/m)	639 ± 381	541 ± 279	577 ± 365	520 ± 269

values are computed with these retained trajectories. Differently, to estimate the relative interaction force and displacement in v_n direction we have used the projection of these two measures, for instance the relative interaction force in v_n direction can be estimated as

$$\Delta f = |\Delta f_x| \cos(\phi_x) + |\Delta f_y| \cos(\phi_y) + |\Delta f_z| \cos(\phi_z),$$

with,

$$\Delta f_x = -\left(f_x(t) - f_x(t_d)\right), \quad t_d < t \le t_u,$$
$$\Delta f_y = -\left(f_y(t) - f_y(t_d)\right), \quad t_d < t \le t_u,$$
$$\Delta f_z = -\left(f_z(t) - f_z(t_d)\right), \quad t_d < t \le t_u,$$

where f_i and ϕ_i correspond the measured force in a specified direction and the angle between the nominal vector and the coordinate directions, respectively ($i = x, y, z$), see Fig. 9 for a sample of measurement with estimated signals. Analogues calculations were carried out to estimate the relative displacement in v_n direction as well.

In addition to the hand-impedance measurements, we also investigate whether there exists any statistically significant trend of change at hand-impedance throughout laparoscopy training and difference between the groups that have been established based on the expertise levels of the subjects.

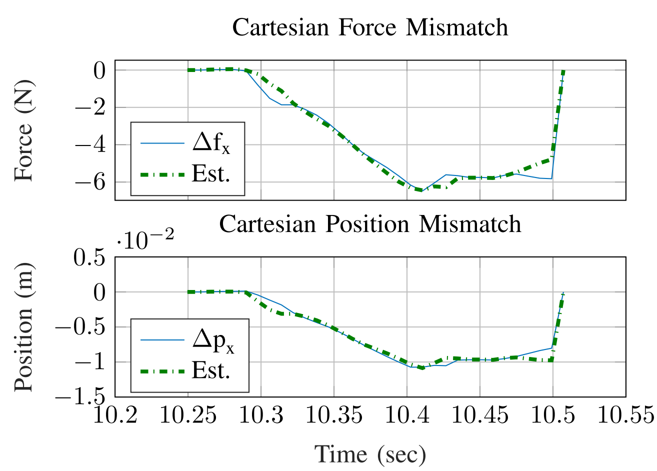

Fig. 9. Force and position mismatches in the direction of disturbance (x). The estimated signals are based on the calculated impedance values with coefficient of determination, r^2, equivalent to 0.8974 and 0.842, respectively. Measured impedance values for this sample: $m_h = 0.019$ kg; $d_h = 3.64$ N s/m; $k_h = 473$ N/m.

4. Main results

The means and standard deviations (σ) of the left and right hands' measured impedances in all the directions are given in Table 2 and rate-hardness values are also illustrated in Fig. 10 for easy comparison. To determine whether there exists any meaningful difference between the impedance measurements among the weeks and expertise levels, we analysed statistical significance of all the estimated data groups (128 in total).

Before the analyses, we first removed the excessive outliers from the data groups by eliminating any measurements that were above (Mean $+ 5\sigma$) and any measurements below (Mean $- 5\sigma$) values [51], then normality tests were carried out for the data groups and we applied Box–Cox transformation[2] to the groups failed within the initial test in order to achieve a normalized distribution in each of the compared groups. Approximately, 94.5% of all the groups passed either the Lilliefors or the Anderson–Darling normality test with a significance level $p = 0.05$ and the data sample size, that executed within the normality test, was > 100. The data groups that failed in the normality tests, despite the transformations, were graphically inspected (via Histograms and Quantile–Quantile Plots) and outliers that jeopardize the normality were ignored in the forthcoming analyses.

[2] The same λ was used for the transformation and the same transformation was applied to the compared groups.

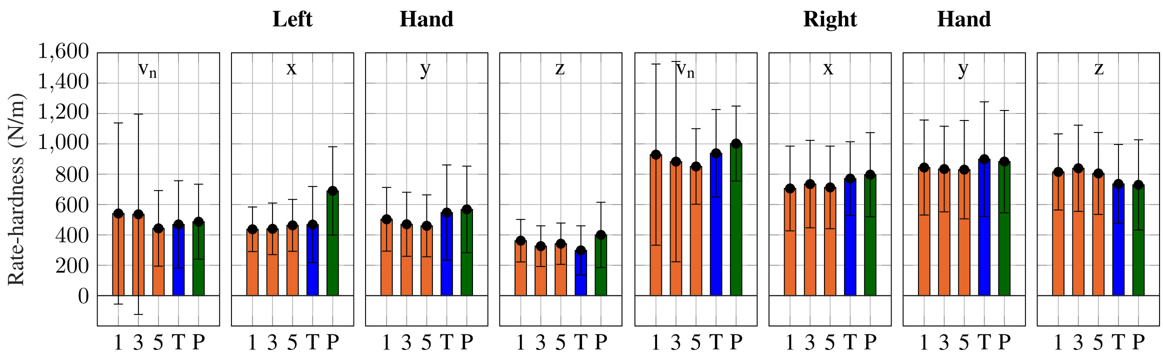

Fig. 10. Measured left and right hands' rate-hardness of the novice (during week 1, 3, and 5), trainee (T), and professional (P) participants.

Table 3
Average performance assessment measures.

	Finished task	Penalization	Total $(T-P)$	Time (min)	opm
	Novice participants in different weeks				
W1	7.85	3.15	4.7	25	0.1880
W3	14.85	2.65	12.2	24.5	0.4980
W5	25.8	1.25	24.55	24.2	1.0145
	Professional and trainee surgeons				
Pro	25.16	3.66	21.5	19.16	1.1221
Trne	25	3.25	21.75	24	0.9062

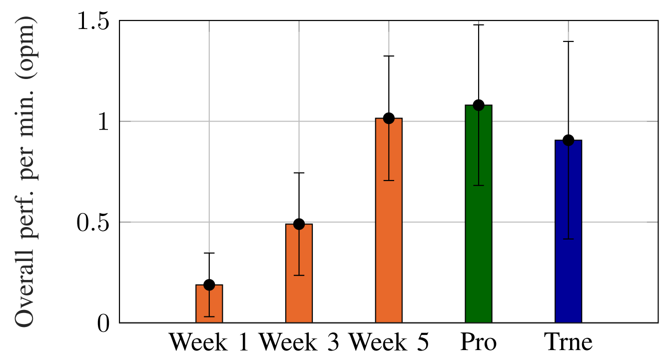

Fig. 11. Average (with standard deviation) overall performance per minute of the novice, professional, and trainee participants.

We applied Welch's t-test (Matlab *ttest2()*) to analyse the impact of expertise with the dual comparisons, such as W3–W5 and professional-trainee correlations, and two-way anova analysis (Matlab *anovan()*) to investigate the impact of two factors on impedance measures: expertise (professional/trainee/novice) and direction ($v_n/x/y/z$) via comparing rh, m_h, d_h, and k_h measures of the professional, trainee, and novice participants. Then, post-hoc analysis was performed with Tukey's test (*multcompare()*) to find the groups that significantly differ from each other with respect to a factor that shows a significant impact. In all the statistical tests throughout the paper, $p = 0.05$ was used as the threshold (maximum) for the statistical significance.

Average performances of all the expertise groups during the experiments are given in Table 3 where an overall improvement is indicated in all aspects with the novice subjects while proceeding throughout the training program. The more illustrative performance comparisons between the groups is shown in Fig. 11 where gradual performance improvement is taking place among the novice subjects and expertise level of the surgeons became apparent. It must be noted that, we do not claim that novice participants have approximately reached the proficiency level of the surgeons after the training program, yet one can state that they simply improved their laparoscopic skills only in a pre-planned suturing practice.

4.1. Statistical analyses among the novice subjects

Initially, we analysed statistical significance difference between the impedance measurements of the novice subjects by focusing on the data based on the Week 3 and Week 5 experiments. We excluded the Week 1 measurements because, as it was the first time they used such a system, it may well be argued that in Week 1 they had mainly focused on how to operate the tools rather then to the task itself.

The obtained results are given in Table 4 where (-) indicates when there is no statistically significant difference between the weeks and $W_5 > W_3$ ($W_5 < W_3$) indicates when there exists statistically significant difference such that mean of the Week 5 measurements is higher (smaller) than the Week 3 measurements.

Table 4
Welch's t-test between **Week 3** and **Week 5**.

	Dir.	rh	m_h	d_h	k_h
Left hand	v_n	–	–	–	–
	x	$W_5 > W_3$	$W_5 > W_3$	$W_5 > W_3$	–
	y	–	$W_5 < W_3$	$W_5 < W_3$	–
	z	–	$W_5 > W_3$	–	–
Right hand	v_n	–	–	–	–
	x	–	–	–	–
	y	–	$W_5 > W_3$	$W_5 > W_3$	–
	z	–	–	–	–

4.1.1. Rate-hardness values

Rate-hardness of the left hand in Week 3 was found to be significantly smaller than the Week 5 measurements in the x direction ($p = 0.019338$). Statistically significant difference is not observed with respect to the right hand.

4.1.2. Mass values

Left hand mass estimations in Week 3 were found to be significantly smaller than the Week 5 estimations in x ($p = 1.38 \times 10^{-4}$) and in z ($p = 0.0103$) directions, yet it was vice versa in y ($p = 2.06 \times 10^{-4}$) direction. On the contrary, the right hand's Week 3 was found to be significantly smaller than the Week 5 estimations in y ($p = 0.0015$) direction.

4.1.3. Damping values

In y direction, there exist statistically significant difference both in left ($p = 4.4 \times 10^{-4}$) and right ($p = 0.0099$) hands' measures; right hand's damping values in Week 5 were higher than the Week 3 values, yet left hand's damping values in Week 5 were smaller than the Week 3 values. But, left hand's damping values in Week 5 were higher than the Week 3 values in x direction ($p = 0.0207$).

Table 5
Welch's t-test between **Professional** and **Trainee** surgeons.

	Dir.	rh	m_h	d_h	k_h
Left hand	v_n	–	–	–	–
	x	$P > T$	$P > T$	$P > T$	–
	y	–	–	–	–
	z	$P > T$	–	–	$P > T$
Right hand	v_n	–	–	–	–
	x	–	$P > T$	$P > T$	–
	y	–	–	–	–
	z	–	–	–	–

4.2. Statistical analyses between the professional and trainee surgeons

Statistical significance difference analyses were carried out among the surgeons by comparing only impedance measurements of the professional and trainee surgeons. With this respect, it was observed that in all the significance difference results the measured mean hand-impedances of the professional surgeons were higher than the trainees' measurements ($P > T$), see Table 5.

4.2.1. Rate-hardness values

In left hand, there exist statistically significant difference both in x ($p = 6.4 \times 10^{-7}$) and z ($p = 0.0009$) directions; rate-hardness values of the professional surgeons' hands were higher than the trainees values.

4.2.2. Mass values

The only statistically significant results were obtained within mass values of the professional and trainee surgeons is in x direction, which is parallel to the suturing line, both with left ($p = 3.4 \times 10^{-7}$) and right ($p = 0.0316$) hands' measurements.

4.2.3. Damping values

As in the mass measurements, the only statistically significant results were obtained within the damping values of the professional and trainee surgeons in the x direction both for left ($p = 9.2 \times 10^{-8}$) and right ($p = 0.0314$) hands.

4.2.4. Stiffness values

The stiffness of the professional surgeons' left arm was found to be significantly higher than the trainees' only in the z direction ($p = 0.0071$).

4.3. Relativity between the impedances of the professional, trainee surgeons, and novice participants

As a final effort, statistical significance analyses were carried out to compare the impedance measurements of the professional, trainee, and novice participants. Based on the overall performance calculations, we have used the Week 5 measurements within the forthcoming analyses to stand for impedances of the novice subjects. Also, for clarity the critical p values for the factors expertise and direction are stated as p_e and p_d, respectively.

4.3.1. Rate-hardness values

For the rate-hardness measures, the two-way ANOVA found significant effect due to the factors expertise (p_e) and direction (p_d) both in left ($p_e = 1.7 \times 10^{-10}$ and $p_d = 4.5 \times 10^{-34}$) and right ($p_e = 0.0402$ and $p_d = 1.7 \times 10^{-5}$) hands and there were significant interactions between these two factors within the both hands. The rate-hardness of the professional surgeons' left hand measure was found to be significantly higher than that of the trainee surgeons x ($p = 4.8 \times 10^{-5}$) and z ($p = 0.0109$) directions. Similarly, it is also significantly higher than that of the novice subjects ($p = 2.9 \times 10^{-7}$) in the x direction. We did not find significant difference between the professional, trainees, and novice participants in v_n and y directions with the left hand measures. Regarding to the right hand measurements, the rate-hardness of the professional surgeons' was found to be significantly higher than that of the novice subjects only in v_n ($p = 0.0081$) direction.

4.3.2. Mass values

The two-way ANOVA analyses found significant effect due to the factors expertise and direction both in left ($p_e = 1.5 \times 10^{-6}$ and $p_d = 1.09 \times 10^{-22}$) and right ($p_e = 2.1 \times 10^{-5}$ and $p_d = 0.0434$) hands within the mass measures, besides there were significant interactions between the two factors within the both hands. The mass of the professional surgeons' left hand measure was found to be significantly higher than that of the trainee surgeons ($p = 6 \times 10^{-7}$) and Week 5 measurements ($p = 5.8 \times 10^{-4}$) in x direction. But, with the right hand, Week 5 has the highest mass measurement in x direction, namely the right hand mass measure in Week 5 was found to be significantly higher than that of the professional ($p = 2.5 \times 10^{-4}$) and the trainee ($p = 2.7 \times 10^{-7}$) surgeons. In y direction, there exists statistical significance difference with left hand mass measures, such that the professional surgeons' measure was found to be significantly higher than that of the novice subjects' ($p = 0.0181$), yet we did not found any significance difference with right hand in the same direction. Similar to that, no significant difference observed in v_n and z directions for the both hands' mass measurements.

4.3.3. Damping values

With the damping measurements, the two-way ANOVA analyses found significant effect due to the factors expertise and direction both in left ($p_e = 5.5 \times 10^{-14}$ and $p_d = 1.06 \times 10^{-111}$) and right ($p_e = 0.0355$ and $p_d = 1.4 \times 10^{-42}$) hands, besides there were significant interactions between these two factors within the both hands. The damping of the trainee surgeons' left hand was found to be significantly higher than that of the novice subjects in v_n direction ($p = 0.0136$), yet no statistical difference observed with the right hand measures in this direction.

As in the mass analyses, the damping of the professional surgeons' left hand measure was found to be significantly higher than that of the trainee surgeons ($p = 3.4 \times 10^{-7}$) and Week 5 measurements ($p = 2.2 \times 10^{-7}$) in the x direction. But, with the right hand, Week 5 has the highest mass measurement in the x direction, namely the right hand damping measure in Week 5 was found to be significantly higher than that of the professional ($p = 8 \times 10^{-7}$) and the trainee ($p = 2.3 \times 10^{-7}$) surgeons. In the y direction, there exists statistical significance difference with left hand mass measures, such that the professional surgeons' measure was found to be significantly higher than that of the novice subject ($p = 0.0167$) and the trainees' measure was found to be significantly higher than that of the novice subject ($p = 0.0018$) as well. Yet, we did not observe any significance difference with right hand in this direction. Similar to that, no significant difference observed in z directions for the both hands' damping measurements.

4.3.4. Stiffness values

The two-way ANOVA analyses found significant effect due to the factor expertise in left hand ($p_e = 3.24 \times 10^{-4}$) and with the right hand due to factor direction ($p_d = 0.0101$) within the stiffness measures, besides there was significant interactions between these two factors only within the right hand.

The Table 6 provides the results obtained from the two-way Anova analyses of the impedance measurements grouped with respect to the expertise level of the participants.

Table 6
Two-way anova test between the **Professional**, **Trainee** surgeons and **Week 5**.

	Dir.	rh	m_h	d_h	k_h
Left hand	v_n	–	–	$T > W_5$	–
	x	$P > T$ $P > W_5$	$P > T$ $P > W_5$	$P > T$ $P > W_5$	–
	y	–	$P > W_5$	$P > W_5$ $T > W_5$	–
	z	$P > T$	–	–	–
Right hand	v_n	$P > W_5$	–	–	–
	x	–	$P < W_5$ $T < W_5$	$P < W_5$ $T < W_5$	–
	y	–	–	–	–
	z	–	–	–	–
Sig. Factors:		Exp. & Dir.	Exp. & Dir.	Exp. & Dir.	Left: Exp. Right: Dir.

5. Discussion

In our measurements, right hand-impedance was consistently found to be higher than the left hand's; Welch's t-test was carried out to compare impedance measurements of the left and right hands ($p \leq 8.2 \times 10^{-19}$ $\forall$ cases) with the data consisting of measurements in Week 5 and experiments with professional and trainee surgeons, see Table 2 as well. We hypothesize a link between that and difference of the left and right hands' instruments that typically require different grasps and therefore have diverse finger and hand postures. Previous research has established that hand-impedance can vary depending on stiffness of the hand grip [24]; this aspect, for instance, is frequently revisited in stability analyses of the bilateral teleoperation systems (see, e.g., [52]).

More number of statistically significant difference in the left hand-impedance parameters was observed compared to the right hand, across the experts and novices within the different levels of training, see Tables 4, 5, and 6. We hypothesize that, this difference might be because the left hand instrument has been used more actively during needle placement and requires better control through both wrist and finger movements.

Statistically significant and consistent difference was observed particularly in the x direction while comparing the expertise levels of all the participant groups. This is the direction, where the subjects were facing, parallel to the suturing line and more or less along the instrument shafts in the Cartesian plane. This consistence difference across the skill levels might be an indicator that the task involves more movements on this axis compared to the other directions.

Among the mass, damping, and stiffness parameters, we found statistically significant differences with mass and damping. However, no statistically significant difference in the stiffness was observed except for a single instant (Table 5, left hand, z direction). Stiffness is related to the active use of muscles and muscle strength. We hypothesize that the experts do not maintain skilled performance due to their muscle strength nor because they activate their muscles more than the others but mostly because they orient their body–arm–hands better than the novice subjects, by adapting a more ergonomic posture, as proposed in [53].

The previous study, [54], indicates that age (< 70) and gender (when eliminating the effect of the bodyweight) have little or no effect on the mechanical impedance characteristics of the human elbow joint. In this initial study, we also neglected the effects of the demographic and anthropometric factors on the impedance of the human upper limps, see [55], for instance, the effect of these factors on the orientational impedances. A future research direction is to investigate the null hypothesis of "gender and age does not affect the hand impedances during laparoscopy".

6. Conclusion

To the best of authors knowledge, the present study has demonstrated, for the first time, hand-impedance measurements of the surgeons and novice subjects in the laparoscopic suturing practice. Also, we demonstrate that the measurements are effective to capture skill related differences across professional laparoscopy surgeons and novice subjects. One can consider that the presented technique and the identified values can be useful for the following purposes in future research: (i) to inform laparoscopy training practices in order to optimally orient the arms to maintain optimal hand-impedance, (ii) to be used in co-manipulated robotic trainers in order to gradually teach to the trainees the optimal hand-impedance, (iii) to provide a biologically based method of assessment of laparoscopy skills with hand-impedance measurements, and (iv) to be used in the stability analysis of the coupled robot–human system in a co-manipulated robotic trainer/assistant application. Current results lead us to the hypotheses, hence, further effort is required to validate aforementioned observations and correlations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Harun Tugal received the B.Sc. degree in electrical and electronics engineering from Karadeniz Technical University, Trabzon, Turkey, in 2011, the M.Sc. degree in advanced control and system engineering and the Ph.D. degree in electrical and electronics engineering from Manchester University, Manchester, U.K., in 2013 and 2017, respectively. He was a Research Associate with the Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, UK. His research interests include bilateral teleoperation, physical human–robot interaction, underwater robotics, and machine learning.

Benjamin Gautier was pursuing a Ph.D. degree with the Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, U.K.

Benjie Tang was appointed as a Lecturer at the Cuschieri Skills Centre, University of Dundee in 2006 and promoted as a Senior Lecturer in 2013. He graduated from Medical School of Qingdao University in 1987, China and did his postgraduate study as clinical fellow in surgery at Medical School of Beijing University in 1997. He obtained his MD from Medical School of Dundee University in 2004. He is a full y qualified general surgeon with interest and extensive experience in laparoscopic surgery. He has interest in use of Human Reliability Analysis (HRA) technique to evaluate laparoscopic surgery to improve surgical performance and patient safety.

Ghulam Nabi is currently a Professor at the Cuschieri Skills Centre, University of Dundee, U.K. He is a fully qualified general surgeon with interest and extensive experience in laparoscopic surgery.

Mustafa Suphi Erden received the B.S., M.S., and Ph.D. degrees in Electrical and Electronics Engineering from Middle East Technical University, Ankara, in 1999, 2001, and 2006. From 2007 to 2012 he was a postdoctoral researcher, successively in Delft University of Technology, the Netherlands; in Ecole Nationale Supérieure de Techniques Avancées-ParisTech, France; in Univ. Pierre & Marie Curie - Paris 6, France. He is an Assistant Professor with the School of Engineering and Physical Sciences at Heriot-Watt University in Edinburgh, UK, since 2015. His research interests include physical human–robot interaction, assistive robotics, skill assistance, mechatronics design, medical robotics, walking robots, and machine learning.