

# Hand-Impedance Measurement During Laparoscopic Training Coupled with Robotic Manipulators\*

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**Abstract**—This paper presents measurements of human hand-impedance during a laparoscopic training program with physically interactive robotic manipulators. The knowledge of how the hand-impedance changes due to training might be useful to inform better training programs and to introduce co-manipulated robotic assistants for effective trainings. Ten novice subjects participated in a three weeks training program for a suturing activity in laparoscopy. The subjects have been instructed to set the needle, enter the skin, and tie knots by using laparoscopic tools within a Minimally Invasive Surgery training box. Variable admittance controlled robots, attached to the tools with force sensors, applied step vice velocity disturbances while subjects were trying to set the needle. Based on the interaction force and end-effector position information, impedances of the left and right hands were computed in four different directions. The computed results were compared with respect to the participants skill progression.

## I. INTRODUCTION

Laparoscopy, a special type of Minimally Invasive Surgery (MIS) also known as keyhole surgery, enables surgeons to perform operations using small incisions leading to minimal surgical wounds, that connotes less post-operative pain and a quicker recovery time for the patients. Improvements within the scaled-down display devices and special surgical instruments give rise to utilization of this technique, evidently it became the main method for the operations around abdominal region such as cholecystectomy, appendectomy, and Nissen fundoplication surgeries [1]. Apart from the aforementioned benefits and acceptance, the laparoscopic technique brings additional challenges to the surgeons as it requires more training to master than a conventional open surgery. The paramount challenge is the disturbed observation along with a loss of depth perception as the operation is viewed on a two-dimensional screen. Also, manipulation is disoriented due to the discrepancy between the hand movements and tip of the laparoscopic tools (the well known fulcrum effect) [2], [3]. To circumvent those difficulties surgeons require to carry out extensive and protracted training programs outside the operation rooms, hereby proficiency is broadly subjectively assessed due to lack of quantitative measurements indicating whether or not a trainee reached a sufficient competence level for the laparoscopy [4], [5].

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Herein, hand-impedance estimation techniques can be embedded within the laparoscopic training kits to distinguish impedances of professional and novice surgeons, in this way learning process within the training program can be optimized by providing appropriate feedback and also possibly robotised co-manipulated assistants to enhance the hand-impedance accordingly.

The muscles, bones, and masses i.e. the musculoskeletal system forming the human hand along with the arm can be associated, all together, as a mechanical system. Dynamical characteristics of this system, in general, described as a mechanical impedance [6]. This characteristic phenomenon is encountered frequently in human-robot interaction such that any slight vibration or oscillation at the point of touch involuntary extinguishes with a hand grip [7]. In addition to this passive behaviour, human hand model is also assumed locally as a Linear Time Invariant (LTI) system consisting of mass, spring, and damper [8]. In this way, not only stability analysis of haptic systems is streamlined but also conservatism within the analysis is reduced by diminishing uncertainties (e.g. hand model) within the overall system.

In the light of the above findings, measuring hand-impedance 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 resulting response behaviour of the hand is extensively revisited methodology, for instance see [9], [10] for the force and [11], [12], [13] for the position disturbances.

Generally speaking, to apply perturbations or measure the hand position admittance controlled robotic manipulators have been used within the aforementioned hand-impedance measurement techniques without concerning the overall system's stability. But, unlike the other cases where this control methodology was revisited, such as manual welding [10], the training for suturing requires frequent contact of the laparoscopy instruments with hard (key hole, the needle, and tip of the other instrument) and soft (the pad to be sutured) structures. Thus, special care should be taken to eliminate the instability that might occur due to such contacts during the training and measurement procedures. Here, we implemented an adaptive admittance control which allows both transparent co-manipulation in normal manipulation conditions and low admittance in case of oscillations during contact.

In this paper contact hand-impedances of the ten participants were computed during a three weeks laparoscopy training program by applying small step-vice velocity disturbances via robotic manipulators. As an initial effort, post-

hoc analyses were also carried out to identify any significant difference between the impedance parameters measured at different periods within the program.

## II. METHODOLOGY

### A. Experimental Setup

The experimental setup consists of one MIS training box, 2 Universal Robots (UR3), and 2 ATI force/torque (FT) sensors. The FT sensors have been inserted between a special mechanical adaptor which was integrated to the MIS tool and the robot's end-effector, see Fig. 1. The UR3 robots are light weight, capable of carrying 3 kg at its end effector, controlled by its own control box providing 125 Hz control cycle. To create a human-robot interaction, an admittance control architecture with variable parameters has been 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).

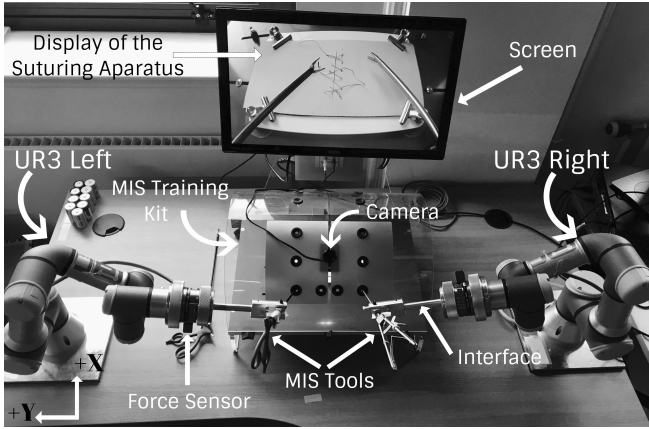


Fig. 1. Experimental setup: MIS training kit with integrated UR3 robots.

### B. Implemented Admittance Control Architecture

The depicted admittance control architecture's block diagram, which is used to experiment a physical human-robot interaction, is illustrated in Fig. 2. The force sensor at the end effector of the robot measures the interaction force with the tool kit and based on this measurement the controller generates the desired velocities. In Cartesian space, the motion dynamics of the admittance controller can be described as

$$F_s = M_a \dot{V}_{ref} + D_a V_{ref}, \quad (1)$$

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

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

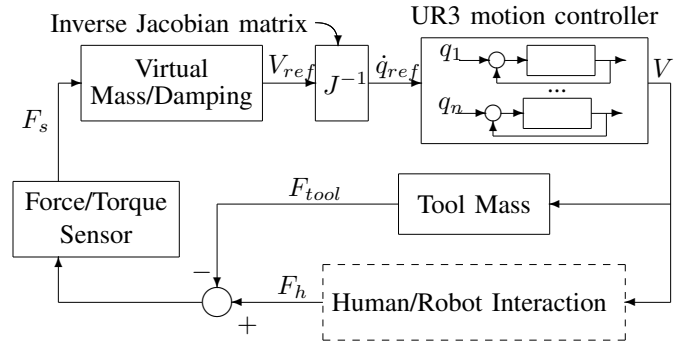


Fig. 2. Block diagram representation of the intended human-robot interaction with implemented admittance control architecture.

Admittance control parameters,  $M_a$  and  $D_a$ , need to be meticulously determined due to the inherent trade-off between the stability and performance. A small admittance corresponds to sufficient elimination of the external force disturbances, yet exhibits sluggish response in the free space movements. In the same manner, a large admittance, with respect to the mechanical driving-point impedance, enables operator to accomplish smooth noncontact movements by giving rise to rapid velocity incline to the applied force, yet that might jeopardize the stability of the overall system [14].

### C. Frequency Analysis of the Laparoscopic Operation with Robotic Manipulators

Generally speaking, dynamics of the intrinsic hand movement is significant over the low frequency range, 0-10 Hz [15]. In a similar manner, the laparoscopic operations require gradual and dedicated hand motions. To quantitatively determine principal frequencies during laparoscopy, initially, we carried out different experimental scenarios where laparoscopic tools either manipulated in a gradual, stable manner or conducted fast and oscillatory behaviour which, in general, can be characterized as undesired, *instable* movements. The stable motions are achieved under high mass and damping parameters within the designed admittance controller, similarly instability is encountered under low admittance control parameters. After running 6 different experimental scenarios both for stable and instable motions (12 in total), we have analysed the interaction forces and Cartesian space velocity measurements in frequency domain by using fast Fourier transform (FFT) [16]. The frequency spectrums of the both signals are illustrated in Fig. 3.

As seen from the frequency spectrums, the principal frequencies of the desired stable motions in the 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,  $\Delta f$ , 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  $\Delta f = \frac{f_s}{N}$ . In addition to the computational load, the price paid for the large value  $N$  is a slower detection for the real time implementation. Hence-

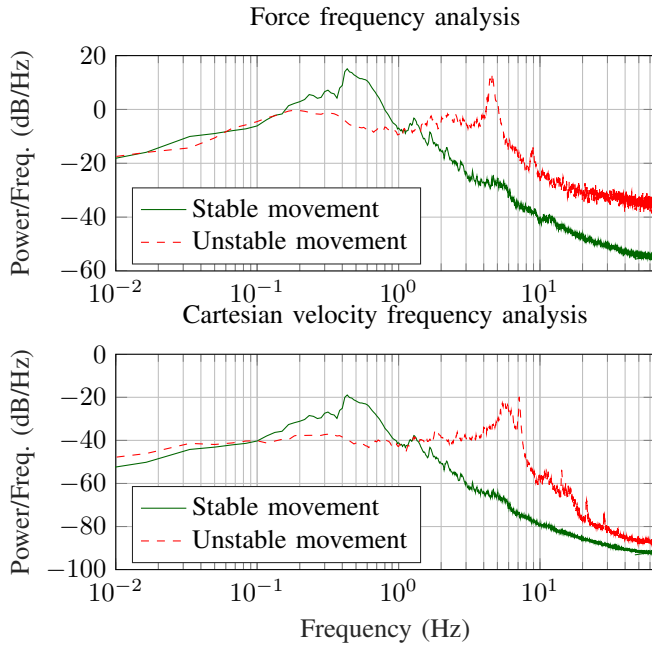


Fig. 3. Power spectral densities of the force and velocity measurements during experimental laparoscopy by using FFT.

forth, we will depict the frequency resolution  $\Delta f = 0.9766$  Hz, by choosing  $N = 128$ , and the critical frequency ( $f_c$ ) as 1.9531 Hz for the laparoscopic operation with the robotic schema. In this way, any movements higher than the critical frequency will be interpreted as an involuntary behaviour. Despite obtaining similar frequency spectrum both with force and velocity measurements, we tend to use force signal in the forthcoming frequency analyses as force becomes the dominant measure when the MIS tool is in contact with its environment, for instance while suturing.

#### D. Empirical Instability Disclosure

Stability, inherently, is the main concern while designing a control architecture for a robotic system interacting with its environment also embedded into a critical application such as robotic surgery training as there is almost no room for any unwanted behaviour. 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 [17], [18].

To assess the stability of a robotic architecture, passivity, a sufficient condition for the stability, is the main technique applied by many researches. This method provides an elegant tool to eliminate severe constraints caused by the unmodelled dynamics of the robotic systems via concerning only the input and output energy of the system [19]. Yet, it should be noted that a major problem within this model avoidance methodology is that the overall design becomes too conservative. To reduce the conservatism one can design passivity observer/controller, introduced as in [20], by using measured forces and velocities to estimate total power/energy injected to the system. Yet, integrated energy during passive motions is the inherent limitation of this methodology;

that phenomenon prevents instant active behaviour detection at real time implementation and requires intuitive energy resetting methodology [21], [22].

More recent attention has also been focused on deriving empirical instability detection methodology via 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. And by distinguishing the desired movements from the undesired behaviour via haptic stability observer (HSO), proposed in [23], unwanted actions can be eliminated via penalization techniques such as an increase in the overall impedance of the system by appropriate control action [23], [24], [25].

Following [23], [25], we designed a variable admittance controller by using HSO index,  $I_p$ , and a recursive stability index,  $I_f$ . Those indices can be determined by analysing robot's velocities/positions or interaction forces in frequency domain via using FFT analysis. A ratio, known as HSO, is depicted by dividing the sum of the amplitudes of unstable frequency components with the sum of the amplitudes of all frequency components and changes in this parameter can be used as a remark to detect the overall instability (or stability).

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

where  $P_f(f)$  and  $f_0$  denote the FFT of the determined signal (force) and the lowest frequency within the FFT, respectively. One can determine the highest substantive frequency component within the FFT analysis based on the Nyquist sampling theorem, where it has been stated that sampling rate must be at least twice of the highest frequency component for correct representation of a signal, that is why it has been limited to  $f_s/2$ . Another, more applicative, recursive stability index is depicted as

$$I_f[kT] = I_p[kT]I_{f_{rms}}[kT] + \lambda I_f[(k-1)T],$$

where  $I_{f_{rms}}$  is the ratio between root mean square and maximum value of the measured force signal and  $\lambda$  is tunable time constant of the index, see [25] for more detailed information. In order to demonstrate how these two indices change with respect to the frequency of the analysed force/torque measures, we carried out an FFT analysis of a force signal with different frequencies and acquired the aforementioned indices. Based on Fig. 3, the critical frequency,  $f_c$ , namely the frequency distinguishing the desired and undesired behaviours is depicted as 1.95 Hz. The preliminary analysis results are illustrated in Fig. 4 where at the first half (0-4 sec) the frequency of the force signal is 1 Hz ( $< f_c$ ), yet it is 2 Hz ( $> f_c$ ) in the second part (4-8 sec).

As shown in Fig. 4, increases in the indices, as desired, correlated to the frequency of the oscillatory behaviour. In this manner one can enhance robustness of the system by associating this phenomenon to an overall impedance increment of the system. Therefore, the admittance control

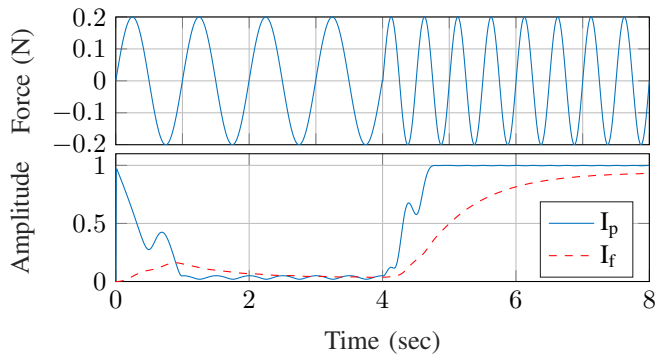


Fig. 4. Alteration of the stability observer parameters,  $I_p$  and  $I_f$  with respect to a force signal in different frequencies.

constants, mass and damping, are designed to be variable parameters and their alteration is associated with the stability indices as

$$\begin{aligned} D_a &= D_{min}I + D_u I_f, \\ M_a &= \frac{M_{min}}{D_{min}} D_a, \end{aligned} \quad (2)$$

where  $M_{min}$  and  $D_{min}$  are minimum virtual mass and damping parameters such that stable free space movement is maintained. 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 controller impedance. It must be noted that, however, there is a certain drawback associated with the use of this haptic stability observer methodology; the instable behaviour cannot be detected before it actually occurs, hence the design required to be able to tolerate initial undesirable behaviours taking place due to the lag within the designed observer.

### E. Subjects and Experiments

Ten novice subjects (5 males and 5 females) took part in our three weeks training program, where experiments and measurements of 5 hours in total per participant took place in Week 1 ( $W_1$ ) and Week 3 ( $W_3$ ). Week 2 was considered to be a training only slot so no measurement was taken during that period. All the subjects were recruited among PhD students of the Institute of Sensors, Signals, and Systems at Heriot-Watt University (HWU), on a voluntary basis. The subjects did not have any prior experience on laparoscopic operation and they used the MIS training kit for the first time during our experiments. All the participants consider themselves as right-handed, yet according to the test result of the Edinburgh Handedness Inventory [26] two of them are actually mixed-handers. The experiment protocol was approved by Ethics Committee of the HWU. All the participants were provided with an information sheet, and they gave their informed consent prior to the experiments.

Before the experiments, the participants were introduced to the MIS training kit and usage of the MIS tools, receiver and driver, they then were instructed about process of the suturing as guided in [27]. The participants were instructed

about how to set the needle, enter the skin with a needle, and tie two different surgeons knots by using the MIS tools. A demonstration of a complete suturing with and without robots were performed by the authors to demonstrate these in practice.

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  $D_{min} = 50$  Ns/m attached to the tools. This phase lasted as long as the subjects got used to the system and felt confident with the tools and robots; it took between 10 and 15 min depending on the subject.

In the experiments, the subjects performed the needle setting process with disturbances. Needle setting is considered to be one of the most difficult and important part of suturing, as a good setting of needle at the tip of the laparoscopy instrument significantly eases the following phases; pushing the needle into the pad and making a knot around the needle. The subjects were informed in advance that disturbances would come from the robots. The disturbances were composed of 100-ms duration 0.15 m/s velocity impulses in one of the eight ( $\pm v_n, \pm x, \pm y, \pm z$ ) directions, randomly applied without replacement, see Fig. 5. Here,  $v_n$  corresponds to the direction perpendicular to the moving plane of the tools (online estimated via end effector positions and its kalman filter estimations),  $x$  corresponds to the direction that the subjects are faced,  $y$  corresponds to the direction perpendicular to the subjects, and  $z$  corresponds to the direction parallel to 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. Each experimental session lasted around 20-25 min.

To assess the progression of the subjects throughout the training, at first glance, we have counted how many times they have completed the needle setting task during the experiments. The number of the needle dropping (on purpose or accidentally) was used as a penalization criterion, thus any unnecessary movements extending duration of the tests were avoided by the participants during the experiments. Subsequently, the overall performance was calculated by subtracting the number of the penalties from the total number of the completed task.

### F. Hand Impedance Estimation

Here, human hand contact impedance is modelled as an LTI passive operator in each of the three main directions ( $x, y, z$ ) and also perpendicular to the moving direction in Cartesian space ( $v_n$ ) decoupled from one another as

$$f_{\Delta}(t) = M_h \ddot{p}_{\Delta}(t) + D_h \dot{p}_{\Delta}(t) + K_h p_{\Delta}(t), \quad (3)$$

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  $p_{\Delta}$  states the position of the hand in Cartesian space. By using measured/calculated data

of force ( $f_{\Delta}$ ), position ( $p_{\Delta}$ ), velocity ( $\dot{p}_{\Delta}$ ), and acceleration ( $\ddot{p}_{\Delta}$ ), the equality in (3) can be solved for estimating the impedance parameters by using the well-known least squares method.

Additionally, we also estimated *rate-hardness* ( $RH$ ) measures in each specified directions as proposed in [28], [10]. We refer reader to [10] for more detailed informations about how to calculate the  $RH$ ,  $f_{\Delta}$ , and  $p_{\Delta}$  values. With these measurements our main goal in this particular paper is to test whether the developed interactive and adaptive admittance control scheme allows for reliable hand-impedance measurements across the subjects. In order to test that we analyse a number of measurement throughout the training and try to observe whether the results are within a meaningful range and consistent with each other. Particularly we would like to have larger impedance values with the dominant hand (right hand) as eight of our subjects are right-handed and two are mixed-handed. Please note that larger hand-impedance is observed with the dominant hands in other studies with a totally different robotic setup and with the task of airbrush painting [29]. The second goal is to make a first attempt to investigate whether we can observe any statistically significant trend of change at hand-impedance throughout laparoscopy training. Observing consistent measures across various measurement would prove the usability of our system. Observing a statistically significant trend would further indicate future directions of research to focus on more refined hand-impedance measurements in specific directions and with one of the right and left hands.

### III. MAIN RESULTS

The average and standard deviations of the measured impedances of the left and right arms in all directions are given in Table I. To determine the existence of any meaningful difference between the impedance measurements from Week 1 and Week 3, we analysed statistically significance of the all estimated data groups (640 in total). Before the analyses, we applied Box-Cox transformation<sup>1</sup> to the all groups in order to achieve a normalized distribution in each of the compared groups. Approximately, 98.2% of all the groups passed either the Lilliefors or the Anderson-Darling normality test with a significance level  $p = 0.05$ . The data groups that failed in the normality tests were graphically inspected (via Histograms and Quantile-Quantile Plots) and outliers that jeopardize normality were ignored in the forthcoming analyses. We applied Students t-test (Matlab `ttest2()`) to the  $W_1$  and  $W_3$  groups. In the all statistical tests throughout the paper, we used  $p = 0.05$  as the threshold (maximum) for the statistical significance.

The average performance of all the subjects at each week is given in Table II where an overall improvement indicated in all aspects as participants proceed throughout the training program. This trend is mainly based on the 90% of the subjects' significant progression, yet we must state that one subject showed no skill improvements due to the difficulty that s/he faced with the loss of depth perception.

<sup>1</sup>The same  $\lambda$  was used within the compared groups for the transformation.

TABLE I  
IMPEDANCE MEASURES IN  $v_n$ -,  $x$ -,  $y$ -, AND  $z$ - DIRECTIONS

Left Hand	Week 1 ( $W_1$ ) Impedances (Avg. $\pm$ Std. dev.)			
	$v_n$	$x$	$y$	$z$
$RH$ (N/m)	541 $\pm$ 597	437 $\pm$ 147	503 $\pm$ 210	362 $\pm$ 140
$M_h$ (kg)	0.022 $\pm$ 0.02	0.023 $\pm$ 0.013	0.03 $\pm$ 0.01	0.017 $\pm$ 0.01
$D_h$ (Ns/m)	7.9 $\pm$ 6.4	6.7 $\pm$ 3.8	13 $\pm$ 5	5 $\pm$ 3.1
$K_h$ (N/m)	357 $\pm$ 304	296 $\pm$ 144	286 $\pm$ 181	310 $\pm$ 143
Week 3 ( $W_3$ ) Impedances (Avg. $\pm$ Std. dev.)				
$RH$ (N/m)	536 $\pm$ 660	440 $\pm$ 170	469 $\pm$ 212	326 $\pm$ 135
$M_h$ (kg)	0.02 $\pm$ 0.017	0.03 $\pm$ 0.01	0.025 $\pm$ 0.01	0.015 $\pm$ 0.009
$D_h$ (Ns/m)	7.8 $\pm$ 5.9	8 $\pm$ 3.8	12.3 $\pm$ 4.4	4.4 $\pm$ 2.7
$K_h$ (N/m)	367 $\pm$ 412	273 $\pm$ 160	297 $\pm$ 187	304 $\pm$ 132
Right Hand	Week 1 ( $W_1$ ) Impedances (Avg. $\pm$ Std. dev.)			
	$v_n$	$x$	$y$	$z$
$RH$ (N/m)	929 $\pm$ 846	706 $\pm$ 280	844 $\pm$ 313	815 $\pm$ 251
$M_h$ (kg)	0.037 $\pm$ 0.03	0.05 $\pm$ 0.02	0.038 $\pm$ 0.02	0.04 $\pm$ 0.02
$D_h$ (Ns/m)	13.7 $\pm$ 7.6	17.4 $\pm$ 6.1	14.6 $\pm$ 7.5	11.6 $\pm$ 6.3
$K_h$ (N/m)	578 $\pm$ 366	359 $\pm$ 207	628 $\pm$ 318	564 $\pm$ 208
Week 3 ( $W_3$ ) Impedances (Avg. $\pm$ Std. dev.)				
$RH$ (N/m)	883 $\pm$ 521	735 $\pm$ 288	834 $\pm$ 282	839 $\pm$ 284
$M_h$ (kg)	0.04 $\pm$ 0.03	0.044 $\pm$ 0.02	0.037 $\pm$ 0.018	0.039 $\pm$ 0.02
$D_h$ (Ns/m)	14.8 $\pm$ 8	15.4 $\pm$ 6.5	15.5 $\pm$ 6.5	10.9 $\pm$ 6.3
$K_h$ (N/m)	560 $\pm$ 337	422 $\pm$ 216	591 $\pm$ 268	600 $\pm$ 234

TABLE II  
AVERAGE PERFORMANCE ASSESSMENT MEASURES

	Finished Task (T)	Penalization (P)	Time (min)	Total (T-P)
$W_1$	7.85	3.4	25	4.45
$W_3$	14.85	2.85	24.5	12

#### A. Rate-Hardness Values

The rate-hardness of the left arm in  $W_3$  was found to be significantly smaller than the  $W_1$  estimations in the  $y$ - ( $p = 0.0296$ ) and  $z$ - ( $p = 0.0013$ ) directions. Yet, we did not observe any statistically significant difference between the left arms'  $W_1$  and  $W_3$  rate-hardness measures in  $v_n$ - ( $p = 0.910$ ) and  $x$ - ( $p = 0.924$ ) directions. Regarding to the right hand, there exist no statistically significant difference in  $v_n$ - ( $p = 0.439$ ),  $x$ - ( $p = 0.176$ ),  $y$ - ( $p = 0.888$ ), and  $z$ - ( $p = 0.255$ ) directions.

#### B. Mass Values

No statistically significant difference was observed between the estimated mass values in  $W_1$  and  $W_3$  both for left ( $p = 0.617$ ) and right ( $p = 0.439$ ) hands in  $v_n$ - direction. In  $x$ - direction, the left hand mass estimations in  $W_3$  was found to be significantly higher than the  $W_1$  estimations ( $p = 0.0083$ ), but it was vice versa with the right hand measures ( $p = 7.83 \times 10^{-6}$ ). Left hand mass estimations in  $W_3$  were found to be smaller than the  $W_1$  estimations both in  $y$ - ( $p = 6.3 \times 10^{-14}$ ) and  $z$ - ( $p = 0.0245$ ) directions. On the other side, no statistically significant difference was observed between the estimated right hand mass values in  $W_1$  and  $W_3$  both in  $y$ - ( $p = 0.375$ ) and  $z$ - ( $p = 0.705$ ) directions.

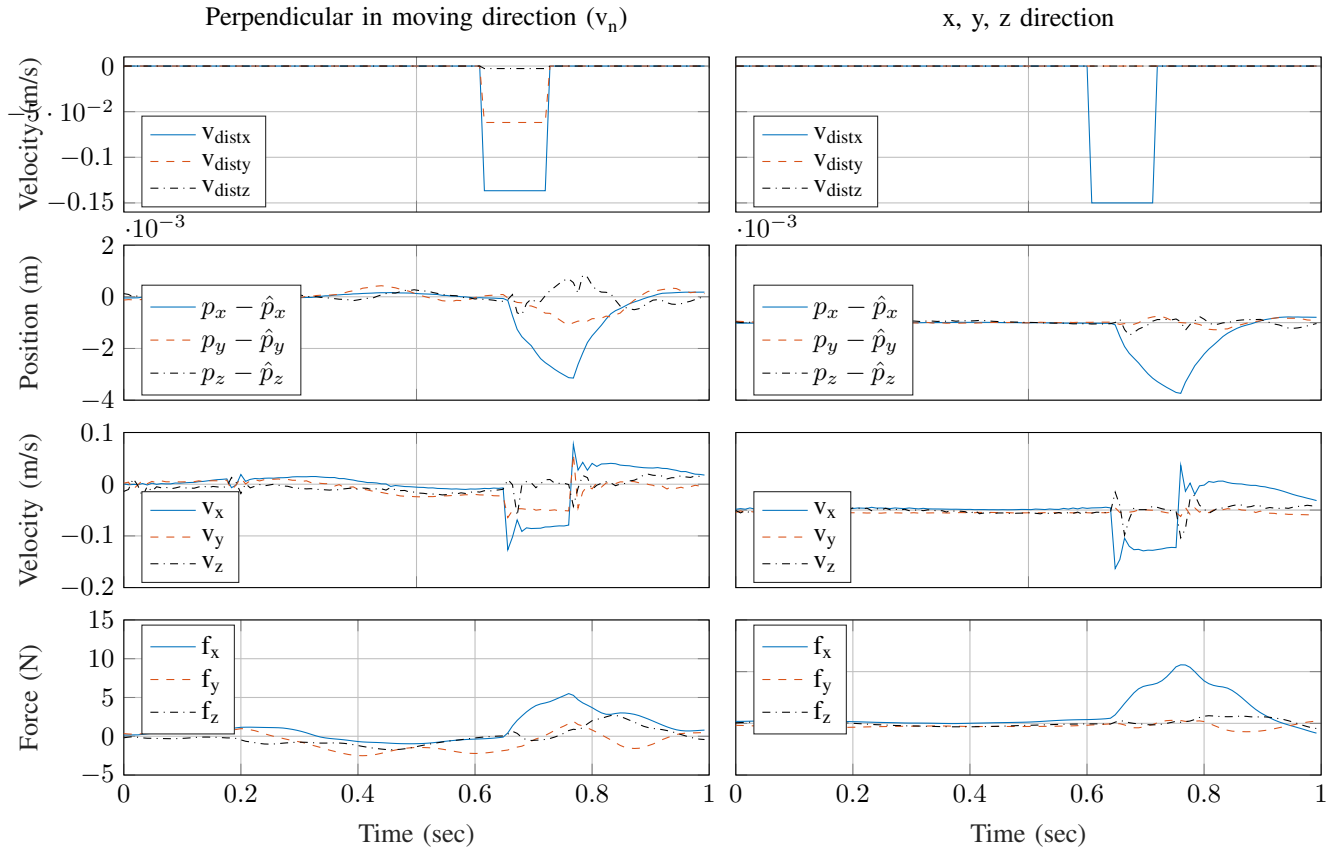


Fig. 5. Data collected from one of the experiments and exclusively zoomed into the disturbance period for the illustration and clarity. The left column shows when a disturbance was applied in  $v_n$ - direction and right column shows when disturbance was applied in  $x$ - direction. Mismatches between 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.

### C. Damping Values

We did not find any statistically significant difference between the estimated damping values in  $W_1$  and  $W_3$  both for left ( $p = 0.966$ ) and right ( $p = 0.1076$ ) hands in  $v_n$ - direction. In  $x$ - direction, there exists statistically significant difference both in left ( $p = 6.7 \times 10^{-6}$ ) and right ( $p = 1.6 \times 10^{-7}$ ) hands' measures; left hand's damping values in  $W_3$  were higher than the  $W_1$  values, yet right hand's damping values in  $W_3$  were smaller than the  $W_1$  values. No statistically significant difference was observed about right hand's damping values in  $y$ -,  $z$ - directions ( $p = 0.063$  and  $p = 0.113$ , respectively) and left hand's values in  $y$ - direction ( $p = 0.083$ ). But, left hand's damping values in  $W_3$  were smaller than the  $W_1$  values in  $z$ - direction ( $p = 0.0336$ ).

### D. Stiffness Values

No statistically significant difference was observed between the estimated stiffness values in  $W_1$  and  $W_3$  both for left ( $p = 0.665$ ) and right ( $p = 0.739$ ) hands in  $v_n$ - direction. In  $x$ - direction, there exist statistically significant difference both in left ( $p = 0.0265$ ) and right ( $p = 3.7 \times 10^{-5}$ ) hands' measures; left hand's stiffness values in  $W_3$  were smaller than the  $W_1$  values, yet right hand's stiffness

values in  $W_3$  were higher than the  $W_1$  values. No difference was observed about left hand's stiffness values in  $y$ -,  $z$ - directions ( $p = 0.432$  and  $p = 0.751$ , respectively) and right hand's values in  $y$ - direction ( $p = 0.243$ ). But, right hand's stiffness values in  $W_3$  were higher than the  $W_1$  values in  $z$ - direction ( $p = 0.0300$ ).

The proposed results are also given in Table III where (–) indicates when there is no statistically significant difference between the weeks and  $W_3 > W_1$  ( $W_3 < W_1$ ) indicates when there exists difference such that Week 3 estimates are higher (smaller) than the Week 1 estimates.

## IV. CONCLUSION

In this study, we implemented an adaptive admittance control scheme leading to a transparent co-manipulation of robotic arms integrated to a laparoscopy training box in order to allow us to measure hand-impedances in a stable manner. This control scheme addresses the specific needs of an interactive robotic system integrated with a training setup, in the sense of adapting the admittance to maintain stable tool movement while occasionally in contact with hard and soft environments within the training box. The measurement results with ten novice subjects throughout a three weeks training indicate that our setup is successful to result in consistent impedance measurements across the

TABLE III  
STATISTICAL SIGNIFICANCE BETWEEN THE WEEKS

	Direction	Left Hand	Right Hand
$RH$	$v_n$	—	—
	$x$	—	—
	$y$	$W_3 < W_1$	—
	$z$	$W_3 < W_1$	—
$M_h$	$v_n$	—	—
	$x$	$W_3 > W_1$	$W_3 < W_1$
	$y$	$W_3 < W_1$	—
	$z$	$W_3 < W_1$	—
$D_h$	$v_n$	—	—
	$x$	$W_3 > W_1$	$W_3 < W_1$
	$y$	—	—
	$z$	$W_3 < W_1$	—
$K_h$	$v_n$	—	—
	$x$	$W_3 < W_1$	$W_3 > W_1$
	$y$	—	—
	$z$	—	$W_3 > W_1$

subjects and a number of different measurements instances. We confirm this especially as we found larger impedance parameters for the right-hand compared to the left-hand with our subjects, eight of whom are right-handed and two are mixed handed. Yet, it also must be noted that the driver is slightly different (mechanically) from the receiver by being heavier and requiring different hand-finger coordination for the operation, thus that discrepancy might have some effects on the impedance measurements and further effort is required to investigate that aspect.

On the contrary, the results do not indicate any statistically significant trend of change in hand-impedance with the three weeks training. The cause of this might be that three weeks training is not sufficient to build an observable change in hand-impedance of novice subjects. In order to test this, we plan a prolonged duration of training and experiment with the same subjects and also plan measurements with the surgeons who have already been trained for the laparoscopy. The differences we would observe in hand-impedance throughout a longer training period and across novice and professional subjects might be used to inform advanced laparoscopy training programs and to build robotic assistants for laparoscopy training.

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