Play Me Back: A Unified Training Platform for Robotic and Laparoscopic Surgery

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***Abstract*—In this letter, we propose a training approach combining hand-over-hand and trial and error training approaches and we evaluate its effectiveness for both robotic and standard laparoscopic surgical training. The proposed approach makes use of the data of an expert collected while using the da Vinci Surgical System. We present our data collection system and how we use it in the proposed training approach. We conduct two user studies (N = 21 for each) to evaluate the effectiveness of this approach. Our results show that subjects trained using this combined approach can better balance the speed and accuracy of their task execution compared with others trained using only one of either hand-over-hand or trial and error training approaches. Moreover, this combined approach leads to the best performance when it comes to the transferability of the acquired skills when testing on another task. We show that the results of the two studies are consistent with an established model in the literature for motor skill learning. Moreover, our results show for the first time the feasibility of using a surgical robot and data collected from it as a training platform for conventional laparoscopic surgery without robotic assistance.**

***Index Terms*—Medical robots and systems, surgical sobotics: laparoscopy, surgical training, training by demonstration.**

I. Introduction

OVER the last few years, robotic surgery has gained popularity because of its many advantages over conventional laparoscopic surgery (which is also referred to as manual or standard laparoscopic surgery) including more intuitive control of the instruments and greater flexibility. While there has been extensive work on transferring conventional laparoscopic skills to robotic surgery, the opposite has not been explored. The fundamental difference between conventional laparoscopic and robotic surgery is the way the surgeon controls his/her instruments. There is a direct mapping between the surgeon's master controllers and the robot's slave arms in robotic surgery. Conventional laparoscopic surgery, however, has an inverted mapping (caused by the fulcrum effect): the surgeon moves the instrument handle to the left (front) to move the instrument tip to the right (back). Laparoscopic training is typically carried out using physical simulators, and more recently, virtual reality and augmented reality simulators. Such simulators cater to the particular needs of laparoscopic training.

In this letter, we aim to answer the following research questions: (i) How can a surgical robotic system be used for training novice surgeons in conventional laparoscopic surgery?; (ii) How can the data collected from surgical tasks on a surgical robotic system be useful for this training?; and (iii) What are the training techniques that can be used in this context?

We propose a complete system that can record and playback surgical robotics data from a standard surgical robot system. Moreover, we propose a training approach using the proposed system to improve the motor skill acquisition for both robotic and conventional laparoscopic surgeries. We evaluate the effectiveness of the system and training approach using two user studies (N = 21 for each) in standard laparoscopic and robotic surgical training tasks. Both studies are conducted using the da Vinci Surgical System as the training platform since it is the most widely used system worldwide with an installed base of approximately 5,000 robots.

In the rest of this letter, we present a literature review of the existing work on training in conventional laparoscopic and robotic surgeries in Section II. We also present our main contributions in the same section. Section III describes the proposed system. Sections IV and V cover the experimental setups, user studies and evaluation metrics used to evaluate the proposed system in conventional laparoscopic and robotic surgery trainings, respectively. The results of the two studies are presented in Section VI and discussed in Section VII. We point out some future directions and conclude the paper in Section VIII.

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II. Related Work and Contributions

A. Training in Surgical Robotics

Several human interfaces have been used for training in robotic surgery. For example, virtual reality simulators have been explored extensively in the literature [1], [2]. In many cases, these simulators are considered the first step of training before letting the trainee use the surgical robots in dry and wet lab environments. Among those simulators are the Robotics Surgical Simulator (ROSS) [3] and the dV-Trainer [4]. Others have also proposed using lower cost interfaces for training. For example, Despinoy *et al.* [5] present a contact-less human interface that uses the Leap Motion sensor for this purpose. Coad *et al.* [6] study the idea of using force fields that can drive the trainees' hands towards the goal location in one case, and away from it in another case. Their work is inspired by the recent results in human motor learning research that point out the benefits of such techniques [7]. In a recent study, Al Fayyadh *et al.* [8] design an auditory and visual interface and test its feasibility in training surgeons to perform a knot tying task. Shahbazi *et al.* [9] propose an expert-in-the-loop training system for dual console surgical systems. Enayati *et al.* [10] evaluate the benefits of providing robotic assistance in robotic surgery training that gradually decreases with the improvement of the trainee's performance. Their results show an improvement in completion time of a training task after using their proposed system. A recent survey of the current status in robotic surgery training can be found in [11].

In spite of this extensive body of literature in robotic surgery training, there are still gaps that need to be filled to realize the full potential of training systems in this area. One of these gaps is the use of the motion data of expert surgeons for robotic surgery training (e.g., in a teach and playback fashion). Using the da Vinci Research Kit (dVRK) [12], we propose using the combination of hand-over-hand training and trial and error training based on an expert's motion data as a way to acquire motor skills in surgical training settings.

B. Training in Conventional Laparoscopic Surgery

Training in conventional laparoscopic surgery is similar to training in robot-assisted surgery [13]. This domain is even more established since conventional laparoscopic surgery is older than robotic surgery by around 20 years. A well-defined training curriculum called the Fundamentals of Laparoscopic Surgery (FLS) was developed by the the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) in 2004 [14]. FLS uses a physical simulator as part of the training curriculum. More recently, virtual reality [15] and augmented reality [16] simulators have also been used. In addition, Chui *et al.* [17] describe a robotic box trainer for conventional laparoscopic surgery. Motion and eye gaze data collected during training and/or real conventional laparoscopic surgery have been mainly used for surgical skill assessment as reported in [18] and for conventional laparoscopic surgery training as reported in [19] and [20]. In [21], the authors develop a training device to record and playback the expert's motion data for manual laparoscopic training, but no study has been conducted to evaluate this approach. In all the above directions, the training platform is always a laparoscopic-like device.

C. Contributions

Our contributions are the following:

- We propose and develop an integrated system that uses the da Vinci API and the da Vinci dVRK for training.
- We propose a new surgical skills training approach that combines hand-over-hand training and discovery training. We evaluate the merits of the proposed approach for both manual laparoscopic and robotic surgical training. Our results show that this combination is better than using only one of these training approaches.
- We study for the first time the feasibility of using a master-slave surgical robot as a training platform for standard laparoscopic surgery. Our results shows the efficacy of using these robotic systems to overcome the fulcrum effect and improve depth perception.
- We show that data collected from robotic surgical training tasks can be useful for standard laparoscopic surgery training as well.

III. Proposed System

A. System Overview

We use the da Vinci Surgical System as our training platform. This system consists of two main units: the surgeon's console and a patient-side cart. The surgeon's console consists of a display system, a user interface, two Master Tool Manipulators (MTMs), and four foot-pedals. The patient-side cart has four patient-side manipulators (PSMs), three of which can be used for teleoperation of surgical tools. The remaining manipulator holds the endoscopic camera. The tools at the PSMs can be considered as extensions of the surgeon's hands controlling the MTMs.

The basic function of the proposed system is to record and playback the motion data along with the views from the surgical console. Since we use the da Vinci surgical system as our case study, this means recording and playing back the motion data of both the MTMs and PSMs. The proposed system consists of two main components: recording and playback as shown in Fig. 1. One advantage of this system is that it can record the data directly from the API interface provided by Intuitive Surgical Inc., and hence we can collect data from any model of the da Vinci system. This makes it possible to collect valuable data during real procedures in the operating room without worrying about the model of the da Vinci. This is unlike using the dVRK which is limited to only the first generation da Vinci or "Standard" model.

In the recording part, the joint angles of both the MTMs and PSMs are acquired. Using these joint angles, the position and orientation of the instrument tip, the master manipulator gripper, and the endoscopic camera position are derived using forward kinematics. All these parameters are then recorded synchronously with the stereovision feed from the endoscopic

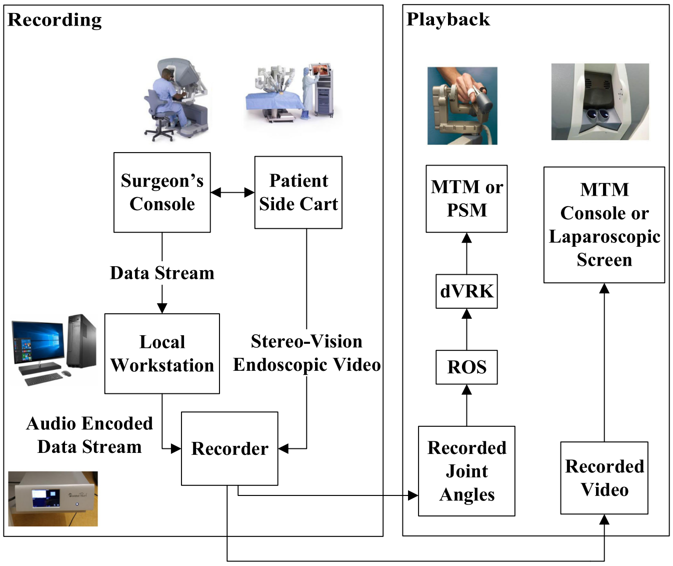

Fig. 1. Overview of the proposed system.

camera. This is done while an expert user performs a surgical training task.

An Epiphan Pearl [22] device is used to record the motion data of the MTMs and PSMs of the da Vinci in a synchronous fashion. The endoscopic videos from the left and right channels of the da Vinci console are captured from the camera module of the da Vinci. Both these channels capture video at a rate of 30 frames per second (FPS). A C++ program is used to interact with the MTMs and PSMs using the API interface provided by Intuitive Surgical Inc., which provides the joint angles, base frame, and DH tables for the MTMs and PSMs. This software also converts the data to a format that can be stored synchronously with the endoscopic video. It interacts with the da Vinci using an Ethernet cable connected to the server port of the robot to read the parameters at a 60 Hz sampling rate. A timestamp is generated with microsecond resolution for each data line. To synchronize the motion data stream with the endoscopic video, the motion data stream is then converted to an audio stream of 48 KHz and sent to the Epiphan through an HDMI cable. After that, a MATLAB script decodes the video to generate the data stream synchronized with the video frame.

In the playback part, the recorded joint angles are fed to a da Vinci Research Kit (dVRK) [12] running on top of the Robot Operating System (ROS), which moves the MTM or the PSM according to the recorded trajectory. A Python script was used to play back the recorded motions. The recorded videos are also shown either on the surgical console at the MTM or on another monitor to be used for robotic and manual laparoscopic surgery training, respectively.

B. Training using the proposed system

We propose using the data collected by the proposed system in the context of surgical training as follows:

1) *Using the surgical console for surgical robotics training*: By playing back the recorded motions of the MTM, a novice user can sit at the console and hold the MTM hand controllers passively. These hand controllers can then guide the user's hands to perform the same recorded task. In addition, by playing back the recorded videos, the novice user can see the same views as in the recording stage.
2) *Using the PSMs for standard laparoscopic surgery training*: In this case, the focus is on the motions of the PSMs. This motion is the same as the ordinary motion of traditional laparoscopic tools. By adding a handle to hold one of the PSMs, a trainee can hold it passively while a recorded motion is played back during a surgical training task. This can overcome some of the hurdles of standard laparoscopic surgery, especially the fulcrum effect [23]. The recorded videos in this case can be viewed on a dedicated screen in front of the trainee.

The next two sections present two user studies ($N = 21$ for each) conducted to evaluate the above training directions. These studies were approved by the Research Ethics Board at the University of British Columbia. In the two studies, the playback part of the training is carried out on a first generation da Vinci system. Unlike the later generations, this da Vinci system is back-drivable. We use small proportional, integral and derivative (PID) gains in the robot controller. Furthermore, the generated forces are not large and hence are not dangerous for the participants, who can easily overcome the PSM. In addition, the emergency stop button is always ready for use by the participant or the supervisor. We, however, did not have to use the emergency stop throughout the conducted studies and we did not encounter any safety concerns with any of the participants.

IV. Standard Laparoscopic Surgery Training Study

The purpose of this study is to evaluate the effectiveness of the proposed system for standard laparoscopic surgery training. To this end, we start first by presenting the experimental setup of the user study. After that, we outline the details of the conducted tests and the performance metrics used.

A. Experimental Setup

Our experimental setup consists of a first-generation da Vinci surgical system equipped with a dVRK, a laparoscopic box trainer, a monitor and a traditional laparoscopic tool as shown in Fig. 2. We added a handle to one of the PSMs to make it easy to hold the robot arm while it is in motion, as shown in Fig. 3. The PSMs of the first generation model of the da Vinci are quite back-driveable, making it easy for the study subjects to move it in any needed direction.

An inanimate task was used during the user study. The task setup, shown in Fig. 4, was placed inside the box trainer. The participants of our study could only see the setup through the dedicated monitor. The task objective was to touch a number of pins in a predefined sequence. The sequence and number of pins were changed in different stages of the user study. The user study participants were asked to touch only the top of the pins. They were instructed to perform the task as fast as they can with the fewest number of errors to avoid the case of moving slowly with the goal of reducing the number of errors. Participants

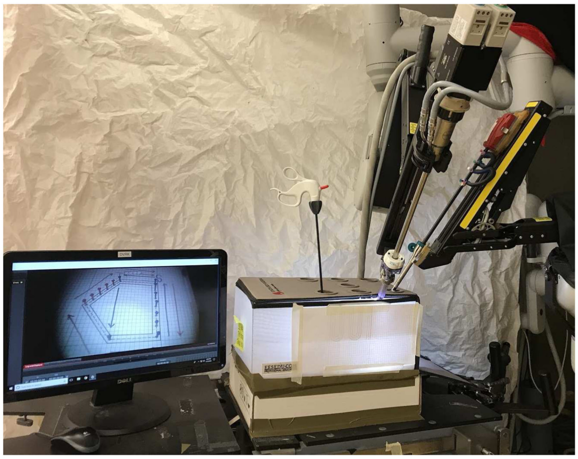

Fig. 2. The full experimental setup of the standard laparoscopic surgery training study: a modified PSM of a first-generation da Vinci is on the right along with the PSM that holds the da Vinci camera. The white handle in the middle is the traditional laparoscopic tool. This tool, along with the camera and the PSMs are all inserted into a laparoscopic box trainer in the middle. A monitor showing what is inside the box is on the left.

Fig. 3. A closer view of one of the da Vinci PSMs after attaching a handle to make it easier for a user to hold.

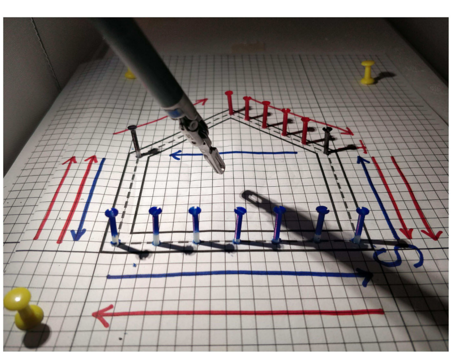

Fig. 4. The task used in the standard laparoscopic training user study was to touch the top of the pins with the end of the tool tip.

were asked to perform the task using the modified PSM of the da Vinci robot in one part of the study and using the traditional laparoscopic tool in the other.

The chosen task is an adapted version of the ball placement task in the Fundamentals Skills of Robotic Surgery (FSRS) validated curriculum [24]. The original task requires the trainee to place a ball on top of several pins. Since the pinching movement of the MTMs is not yet actuated (and hence cannot be played back), we adapt this task to the pin touching one. This task requires several skills that are essential in laparoscopic surgery. The first skill is to overcome the fulcrum effect. The second skill is the depth perception based only on visual feedback. The purpose of the training process is to improve these skills while performing the task in a fast and accurate manner.

B. *User Study*

We recruited 21 participants from University of British Columbia students who had no prior experience with robotic or manual laparoscopic surgery. We also asked an expert user to carry out the chosen task whenever needed in the study. Our ultimate goal was to see if training using one of the da Vinci PSMs would improve the trainees' performance while using the traditional laparoscopic tool.

To begin with, our 21 participants were introduced to the experimental setup via verbal briefing. They were allowed five minutes to familiarize themselves with the movement of the PSM and the laparoscopic tool by performing simple translational movements of their own choice. After that, all participants performed two baseline trials of the training task. The first one was performed using the traditional laparoscopic tool. The second one was carried out using the da Vinci robot arm with the handle attached to it. Following this, the participants were divided into three groups to be trained separately for six trials each (using only the da Vinci robot arm). We chose six training trials based on a preliminary study with another group of participants to see when their performance saturates after trial and error training. On average, the number of training trials to reach this saturation was six.

In the training phase in our study, the 21 participants were divided into three groups of seven as follows:

1) *Discovery Group:* Their training was purely discovery training, i.e., they learned to execute the training task by themselves through trial and error. The trainees in this group were allowed to train for six trials (by performing the training task six times) before the evaluation phase.
2) *Playback Group:* This group learned via the hand-over-hand approach. An experienced da Vinci user teleoperated the PSMs from the surgeon's console to carry out the task. The trainees were asked to hold the handle of the PSM passively while watching the camera view through a dedicated monitor of what the expert was seeing during the task execution. This was repeated six times.
3) *DisPlay Group:* This group had both discovery and playback trainings. They were allowed to train six times. Out of these, *the first one* was discovery training, *the next three*

trials were playback training, and *the last two* were discovery training again. The reason behind this sequence is that we wanted to give the participants of each group the opportunity to explore the best strategy to perform the task before and after being exposed to an expert's execution of it.

After the training, all participants performed two test trials on the same task, to evaluate the training outcome. The first trial was performed using the da Vinci robot arm to measure the improvement in performance. In the second evaluation trial, the study participants used the traditional laparoscopic tool. The purpose of this second evaluation trial was to measure if acquired skill using the da Vinci arm was transferable to the traditional laparoscopic tool.

The participants were also asked to complete two test trials of a variation of the training task to evaluate the skill transferability of each training mode. We call this modified task the *testing task*. Again, the first of these trials was performed using the da Vinci PSM and the second was carried out using the traditional laparoscopic tool.

C. Performance Metrics

We used the following as performance metrics:

- *Completion time:* This is the time taken by the trainee to complete a task. We compared the completion time of the baseline trial and the evaluation trial for each trainee. The lesser the completion time the better.
- *Number of errors:* The errors we refer to in this context are the cases in which the trainee touches any part of any pin other than the top of it. We also counted any missed touch as an error. The number of these errors was counted from the recorded videos of the training and testing trials.
- *Completion time multiplied by the number of errors:* A trainee may move slowly to avoid making any errors. However, this is not always desired. In our study, trainees were asked to execute the task in the shortest time with the fewest number of errors. To reflect that, we used the completion time multiplied by the number of errors as one of our performance metrics similar to the case in [25]. The lower the value of this metric, the better.

V. Surgical Robotics Training Study

This study was conducted to evaluate the effectiveness of our proposed system for robotic surgery training.

A. Experimental Setup

We used two da Vinci robots in this study. The first one was a first-generation da Vinci with a dVRK at which the expert's motion and camera views were recorded and played back. The playback was carried out for the MTMs only and trainees watched the motion of the PSMs in the console from the recorded camera views. The rest of the study was carried out using a da Vinci S system. The master consoles of these two da Vinci robots are very similar and our participants did not feel any difference controlling the two.

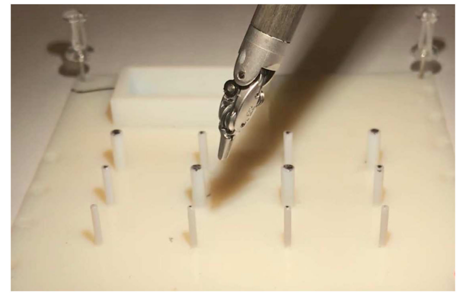

Fig. 5. The surgical robotics training task.

B. User Study

We conducted a study to evaluate the effectiveness of our training framework in surgical robotic training task. We recruited another 21 study participants from University of British Columbia who had no prior experience with the da Vinci surgical system. After verbal and video briefing, the participants had five minutes to familiarize themselves with the system. After that, all participants performed a baseline trial of a training task by controlling the da Vinci MTMs. The task was to touch pins in a predefined order using the PSM tool tip as shown in Fig. 5. We also recorded the robot's data while an expert user executed this task.

We used a pin touching task in this study as well because it involves skills related to robotic surgery such as depth perception, maneuvering the da Vinci tools and getting used to the lack of haptic feedback. We used another pin board in this study whose pins have variable thicknesses. This is to make the task more challenging because the PSM in this case follows the movements of the participants hand, eliminating the fulcrum effect in the manual laparoscopic case.

The participants were divided into three groups of seven: a discovery group, a playback group and a DisPlay group. Each group had four training trials before evaluation. We chose four trials in the same way as we did in the standard laparoscopic training study. The *discovery group* underwent purely discovery training, learning to execute the training task by themselves through trial and error. The *playback group* were asked to hold the hand controllers of the MTM passively while playing back the recorded motion of an expert doing the same task. At the same time, the group watched a video through the console of what the expert was seeing during the task execution. The *DisPlay group* had both discovery and playback trainings. Out of their four training trials, the first one was for discovery training, then the next two were for playback training, and the last one was for discovery training.

After that, all participants performed a final test trial of the training task. We also asked them to do a test trial of a slightly modified task (by changing the order of touching the pins) to evaluate the skill transferability of each training mode.

C. Performance Metrics

We used the same metrics of the standard laparoscopic training study as described in IV-C.

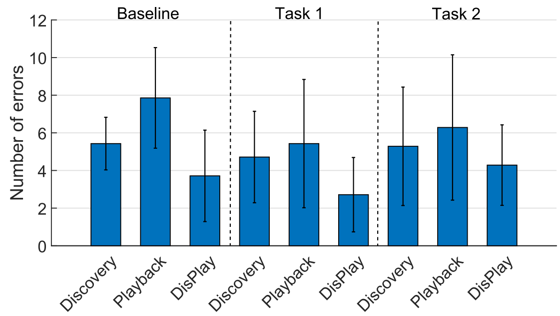

Fig. 6. The number of errors made in the standard laparoscopic surgery training study (N = 21) using the laparoscopic tool in the baseline task, the same task after training (task 1) and the testing task (task 2).

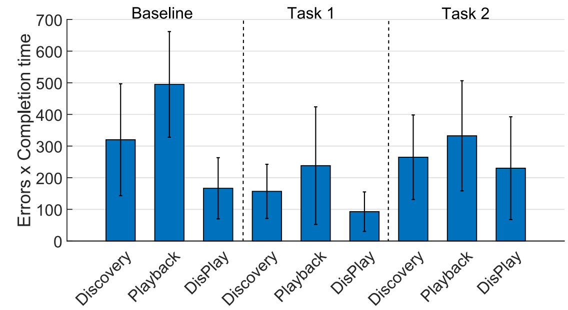

Fig. 8. The performance of the three groups of the standard laparoscopic surgery training study (N = 21) using the laparoscopic tool in terms of the total number of errors multiplied by the completion time.

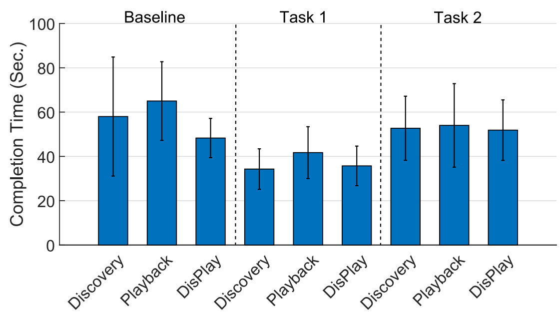

Fig. 7. The completion time in the standrad laparoscopic surgery training study (N = 21) using the laparoscopic tool in the baseline task, the same task after training (task 1) and the testing task (task 2).

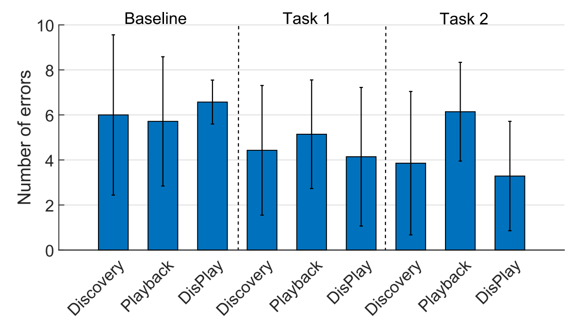

Fig. 9. The number of errors made in the robotic surgery training study (N = 21) in the baseline task, the same task after training (task 1) and the testing task (task 2).

VI. Results

A. Standard Laparoscopic Surgery Training Study Results

Overall, there has been an improvement in the training task performance based on all the chosen metrics using both the modified PSM and traditional laparoscopic tool for all the three groups. Because of space limitations, we report the results of the laparoscopic tool only since the ultimate goal is to improve the performance of using it.

Figs. 6 and 7 show the results of our approach. Overall, there is a noticeable decrease in the number of errors and completion time in all the three groups in their first task after training compared with their baseline performance.

In terms of committed errors as shown in Fig. 6, the DisPlay group makes the fewest number of errors ((3 ± 2) errors on average) in the training task (task 1) which is approximately 40% better than the other two groups. The playback and DisPlay groups show the best improvement compared with the baseline performance by making approximately 31% and 27% fewer errors, respectively, compared with only 13% for the discovery group. For the second evaluation task (the testing task), the DisPlay group is the best, making on average 4 ± 2 errors, which is about 20% better than the discovery group and approximately 33% better than the playback group.

In terms of completion time as shown in Fig. 7, the three groups show comparable performance in the training task with the discovery group having slightly better completion time of 34 ± 9 s on average compared with 36 ± 9 s for the DisPlay group and 41 ± 12 s for the playback group. Compared with the baseline performance, the discovery group shows the best improvement after the training by approximately 41% compared with 36% and 26% for the Playback and DisPlay groups, respectively. For the second evaluation task, the three groups show comparable performance in terms of completion time. The DisPlay group finishes the task in 52 ± 14 s on average. This is similar to the discovery group that needs on average 53 ± 14 s. The playback group is slightly worse, finishing in 54 ± 19 s on average.

Fig. 8 shows the performance of the three groups according to our last metric, that is the multiplication of errors and completion time. The figure shows that in both the training (task 1) and testing (task 2) tasks the DisPlay group is the best, i.e., participants of this group are the ones who move faster with the tool and at the same time commit the fewest number of errors.

B. Robotic Surgery Training Study Results

Figs. 9 and 10 show the results of our approach. Overall, there is a noticeable decrease in the number of errors and completion time in all the three groups in their first task after training compared with their baseline performance.

In terms of committed errors as shown in Fig. 9, the number of errors is comparable among the three groups in the training task (task 1). The DisPlay group, however, shows the best improvement compared with the baseline performance by making approximately 37% fewer errors compared with 27% and only 10% for the discovery and playback groups, respectively. For the second evaluation task, the DisPlay group makes on average

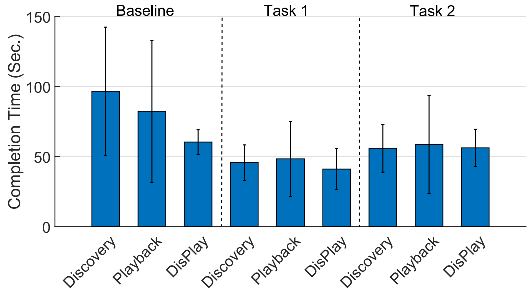

Fig. 10. The completion time in the robotic surgery training study (N = 21) in the baseline task, the same task after training (task 1) and the testing task (task 2).

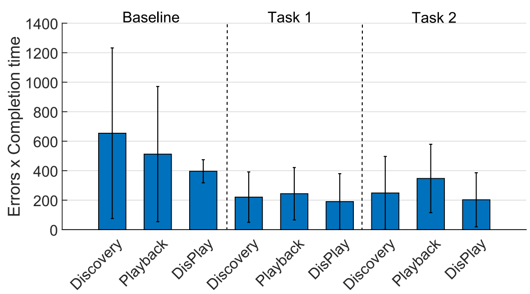

Fig. 11. The performance of the three groups of the robotics surgery training study (N = 21) in terms of the total number of errors multiplied by the completion time.

3 ± 2 errors, which is 25% better than the discovery group and 50% better than the playback group.

In terms of completion time, the three groups show comparable performance in the training task with the DisPlay group having slightly better completion time equals to on average 41 ± 15 s. This time is 15% and 11% better than the times of the playback and discovery groups, respectively. For the second evaluation task, the three groups show comparable performance in terms of completion time. The DisPlay group finishes the task in 56 ± 13 s on average. This is similar to the playback group that needs on average 56 ± 17 s. The discovery group is slightly worse, finishing in 59 ± 35 s on average.

In terms of the multiplication of errors and completion time, Fig. 11 shows that the DisPlay group is the best group in performing the training (task 1) and testing (task 2) tasks. This means that the subjects in this group are the best in both speed and accuracy compared with the other two groups.

C. Statistical Analysis

We perform hypothesis testing using a t-test to verify that the results before and after training are significantly different for each training group in terms of the multiplication of the errors and completion time. For the robotics surgery training study, there is a statistical significance ($p < 0.05$) in the display group only, supporting that it is better than the other two approaches. For the conventional laparoscopic surgery training study, there is statistical significance in both the discovery and playback groups only ($p < 0.05$), which shows the feasibility of using the da Vinci as a training platform for conventional laparoscopy.

VII. Discussion

The results of the two user studies show that combining the playback and discovery training (as in the DisPlay group) leads to the best accuracy compared with the case of having any one of these training approaches alone. Although this combination is not the best in increasing the speed of carrying out the task, it is the best in finding the sweet spot between performing the task fast and at the same time maintaining a good level of accuracy. The same conclusion applies to the unseen tasks; the Display group shows the best transferability of the acquired skills to these types of tasks in both the robotic and standard laparoscopic surgical training studies.

One way to explain these conclusions is through the motor skill learning literature. In [26], Fitts and Posner describe a model for skill acquisition. Their model proposes three stages for acquiring a motor skill: the cognitive stage, associative stage and autonomous stage. In the first stage, a trainee explores the task and tries out several strategies to perform it. This results in high cognitive load as well as highly variable performance. After finding a good strategy, the trainee moves to the associative stage at which he/she tries to refine the strategy to improve the task performance. In the last stage, the autonomous stage, the trainee can perform the task more accurately with less cognitive load. This allows the trainee to focus on other aspects such as transferring the acquired skill to a modified task.

Applying the above model to the studies in this letter, we can understand why the DisPlay group is the best in most of the performance metrics. In this group, subjects are exposed to the best strategy to carry out the task early on in the training process using the hand-over-hand (playback) training approach. This eliminates the time and cognitive load needed in the cognitive stage. This is unlike the discovery group who do not know what the best strategy is and hence they need more time to figure it out themselves through trial and error during their entire training process. Since the kinematics of the expert's hands in our studies is not necessarily the same as all the trainees, the subjects of the DisPlay group are then offered some time to adjust the strategy they got from the playback training for their own kinematics. This happens during the discovery training trials they are offered right after the playback ones. This is similar to the associative stage in Fitts and Posner's model. The playback group, however, do not have the same opportunity as they are only exposed to best strategy for the expert with no room to adjust it for themselves. All this leads to a better performance for the Display group in the autonomous phase in the model compared with the other two groups who may either need more time to find the best strategy to perform the task (as in the discovery group) or need time to adjust the best strategy on their own (as in the playback group). Thus, the DisPlay group can focus more on transferring the acquired skills to the testing task compared with the other two groups.

VIII. Conclusion and Future Work

In this letter, we proposed a training approach combining both hand-over-hand training and discovery training. We proposed a system that can record and playback motion and video data from surgical robotic tasks. We then showed how the proposed training approach and the collected data can be used to improve the motor skills of trainees in standard laparoscopic as well as robotic surgeries. All the training was conducted using the da Vinci surgical robotic system. We conducted two user studies to evaluate the effectiveness of the proposed system and training approach for standard laparoscopic and robotic surgeries. The results of both studies showed that the combination of hand-over-hand and discovery training leads to better performance in performing tasks in terms of accuracy. Trainees using this combined approach were able to balance both the speed and accuracy of performing the task better than those trained using only one of these approaches alone. The results also showed that this combination makes it easier to transfer the acquired skills to unforeseen tasks. We showed how these results are consistent with the motor skill learning literature. Moreover, our results showed the feasibility of using the da Vinci robot, and the data collected from it, as a training platform for standard laparoscopic surgery.

We believe that the results of this letter open up several directions for future research. First, a more extensive user study with more participants and more challenging tasks is needed to validate our results. In addition, it is also important to verify the results on surgical residents. Second, other interaction modalities can be added to the proposed system to improve the training efficiency. This includes recording and playing back the eye gaze data of an expert, adding it to the motion data to see if this would make the training more efficient. This is inspired by nonsurgical training techniques such as quiet eye training in sports [27], which show promising results when applied to surgical training [28]. Furthermore, it would be interesting to explore ways to record and playback specific important movements such as pinching of the surgical instrument which we could not collect using the current system as it is not actuated. Besides, a promising future direction would be modifying the proposed system to collect several demonstrations from different experts and combine them to get a better demonstration than each one alone. In addition to surgical applications, we believe that systems such as the proposed one in this letter augment the increasing interest in using systems such as the da Vinci Surgical robot as a platform for neuroscience researchers to study surgeons' motions in real life scenarios [29].

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