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

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ABSTRACT

In this paper, we propose a modification of the current surgical robot interfaces by adding record and playback buttons. We present a system that can use these buttons to record the robot's motion data during a surgical task. We apply our work to the da Vinci Surgical System. We envision two novel interactions with surgical robots using our modification. The first one is for training novices on surgical robots and the second is training for standard laparoscopic surgery, all on one unified platform. We conduct a user study to evaluate the effectiveness of the proposed system in the second case. Our results show that using the proposed system, trainees can perform surgical tasks faster with lesser number of errors compared with trial and error training. We also show that their acquired skills are transferable to previously unseen tasks.

CCS CONCEPTS

• **Human-centered computing → User interface design**; **Empirical studies in interaction design**; • **Computer systems organization → Robotics**;

KEYWORDS

Robotic Surgery, Laparoscopic Surgery, Surgical Training

1 INTRODUCTION

Over the last few years, robotic surgery has gained popularity because of its many advantages over laparoscopic surgery including more intuitive control of the instruments and greater flexibility. While there has been extensive work on transferring laparoscopic skills to robotic surgery, the same cannot be said for the opposite direction. The fundamental difference between laparoscopic and robotic surgery is the way the surgeon controls his instruments. There exists a direct mapping between the surgeon's master controllers and the robot's slave arms in robotic surgery. On the other hand, laparoscopic surgery has an inverted mapping; the surgeon moves the instrument handle to the left to move the instrument tip to the right. 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.

Figure 1: The surgeon at the console and the patient cart of the da Vinci Surgical System.

In this paper, we aim to answer the following research questions: (i) How can a standard surgical robotic system be used for training novice surgeons in laparoscopic surgery? (ii) 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 simple yet effective modification for the current interface of a robotic surgery system. The modified interface consists of two new buttons that will allow the user to record the motions of the surgical tools and play it back as needed. Using this simple modification, we envision two novel interactions between surgeons and master-slave like surgical robot systems. The first interaction is in the context of surgical robotics training and the second one is for standard laparoscopic surgery training using the same surgical platform. We apply our modification to the interface of the da Vinci Surgical System which is the most widely used system worldwide with more than 4,000 robots all over the world.

A typical da Vinci Surgical System consists of two main units: The surgeon's console and a patient-side cart as shown in Fig. 1. The surgeon console consists of a display system, a user interface, two Master Tool Manipulators (MTMs), and four foot-pedals. The Surgeon visualizes the stereoscopic images of a camera at the patient's side via a display at the console. The foot pedals provide the functionality of restoring the MTM position, changing the endoscopic camera position and other capabilities. The patient-side cart has four patient-side manipulators (PSMs), three of which can be used for teleoperation of surgical tools. One of the manipulators

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holds the dedicated endoscopic camera. The da Vinci system is based on the master-slave technique, where the surgeon uses the MTMs at the surgeon's console to control the movement of the PSMs. The tools at the PSMs can be considered as extensions of the surgeon's hands controlling the MTM.

We hypothesize that with the proposed interface modification, the da Vinci can be used as a unified platform for training in both standard laparoscopic and robotic surgeries. As a case study, we conduct a user study in which we train participants with the modified da Vinci surgical system after adding record and playback buttons and test their skills with a standard laparoscopic training kit. The training is administered using data collected from an expert user of the da Vinci in normal use. The collected data is an expert's motion data of the master manipulator.

Our contributions in this paper are the following:

- We introduce the addition of record and play back buttons to the design of current surgical robotic systems.
- We propose novel interactions between surgeons and surgical robotic systems based on the addition of the above buttons. One of those interactions is for training for surgical robotics and the other for training for standard laparoscopic surgeries.
- As a case study, we evaluate the second proposed interaction in an extensive user study that shows the merits of adding these proposed buttons in the context of laparoscopic surgical training. We also point out further research directions based on the proposed interface.

In the rest of this paper, we present a brief literature review of the existing work on training in laparoscopic and robotic surgeries in Section 2. Sections 3 describes the proposed system and the novel interactions introduced. Section 4 covers the experimental setup, user study and evaluation metrics. Section 5 presents and discusses the results of our user study. We point out some future directions and conclude the paper in Section 6.

2 RELATED WORK

2.1 Training in Surgical Robotics

Several human interfaces have been used for training in surgical robotics. For example, virtual reality simulators have been explored extensively in the literature. In many cases, these simulators are considered the very 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) [19] and the dV-Trainer [9]. Others have also proposed using lower cost interfaces to perform the training. For example, Despinoy *et al.* [7] present a contact-less human interface that uses the Leap Motion sensor for this purpose. Motivated by the lack of haptic feedback, several studies propose ways to overcome this problem. 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 [17]. In a recent study, Al Fayyadh *et al.* [3] design an auditory and visual interface and test its feasibility in training surgeons to perform a knot tying task. Kohen and Kuchenbecker [14] show the feasibility of using the tool vibrations and auditory feedback to compensate for the lack of haptic feedback for both surgeons and non-surgeons in dry lab experiments. Furthermore, Shahbazi *et al.* [20] proposed an expert-in-the-loop training system for dual console surgical systems. A recent survey of the current status in robotic surgery training can be found in [21].

With this extensive body of literature in surgical robotics 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 an expert surgeon for training (e.g., in a teach and playback fashion). The lack of studies in this area is probably due to the need to modify the control system of the da Vinci Surgical System. With use of the da Vinci Research Kit (dVRK) [13] (that is currently available for around 30 research groups worldwide) in the Robotics and Control Laboratory at the University of British Columbia, we propose the addition of record and playback buttons to the current da Vinci interface to enable this training technique.

2.2 Training in Laparoscopic Surgery

Training in laparoscopic surgery follows similar directions as robotic surgery. This domain is even more established than robotic surgery as laparoscopic surgery is older than robotic surgery by around 20 years. The extensive use of this type of surgery results in a well-defined training curriculum called the Fundamental of Laparoscopic Surgery, developed by the the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) in 2004 [18] which uses a physical simulator as part of the training curriculum. More recently, virtual reality [4] and augmented reality [15] simulators are also being used. In addition, Chui *et al.* [5] describe a robotic box trainer for laparoscopic surgery. Data collected during training and/or real laparoscopic surgery have been mainly used for surgical skill assessment like the case in [2] and for surgical training like the case in [22]. Other research are inspired by the use of eye gaze data in areas like sports training [23], [24], and they explore its benefits in laparoscopic surgery training such as [8] and [22].

In all the above directions, the training platform is always a laparoscopic-like device. We are not aware of any work that presents the idea of using a surgical robotic system (like the da Vinci) as a training platform for laparoscopic surgery. In addition, up to our knowledge, no one has proposed the idea of using the data collected using the da Vinci in a robot-assisted surgery for laparoscopic training.

3 PROPOSED SYSTEM

3.1 System Overview

The basic idea of the proposed system is to modify a surgical robot's interface so that the users can record and playback the motion data. Since we use the da Vinci surgical system as our case study, this means recording and playing back the motion data of both the MTM at the surgeon's console and the PSM at the patient-side cart. The proposed system consists of two main components: recording and playback as shown in Fig. 2.

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.

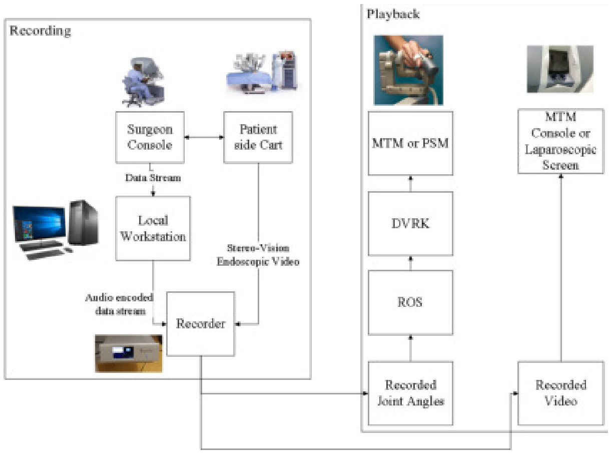

Figure 2: Overview of the proposed system.

All these parameters are then recorded synchronously with the stereovision feed from the endoscopic camera. This is done while an expert user performs a surgical training task. *In the playback part*, the recorded joint angles are fed to a da Vinci Research Kit (dVRK) [13] running on top of the Robot Operating System (ROS), which moves the MTM or the PSM according to the recorded trajectory.

3.2 Novel Interactions

We envision two novel interactions for surgical robots using the above system. These interactions make use of the recorded motion data 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 do the same recorded task. In addition, by playing back the recorded videos, the novice user can see the same views as the recording stage.
2. **Using the PSMs for standard laparoscopic surgery training**: In this case, the focus is on the motions of the PSM. 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 facilitate overcoming some of the hurdles of the acquisition of standard laparoscopic surgery, especially the fulcrum effect [11]. The recorded videos in this case can be viewed on a dedicated screen in front of the trainee. In addition to the screen, a complete training setup should also include a traditional box trainer into which one of the PSMs along with the camera are inserted. The training task should then be done inside this box.

In our previous work [1], we conduct a preliminary study that shows the effectiveness of the first novel interaction for novice training. In this paper, we conduct a user study to evaluate the second proposed interaction and report its results.

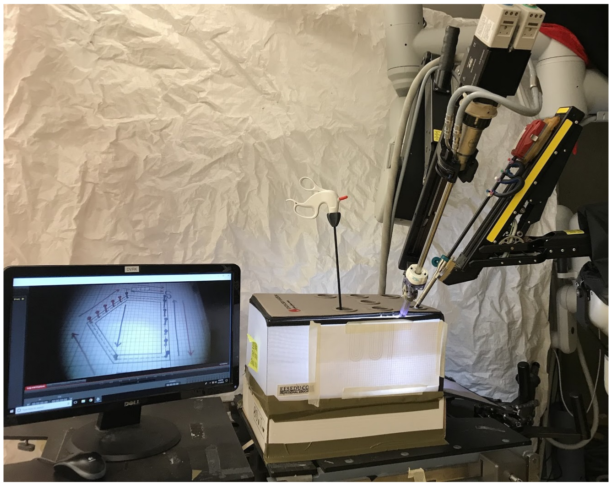

Figure 3: The full experimental setup: a modified da Vinci PSM is on the right along with the PSM that holds the da Vinci camera. The white handle in the middle is the traditional laparoscopic tool. This tool along with the camera and the PSMs are all inserted into a box trainer in the middle. A monitor showing what is inside the box is on the left.

4 EXPERIMENTAL EVALUATION

In this section, we present the details of the conducted user study. The main purpose of these studies 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.

4.1 Experimental Setup

Our experimental setup consisted of a da Vinci surgical system equipped with a dVRK, a box trainer, a monitor and a traditional laparoscopic tool as shown in Fig. 3. We added a handle to one of the PSMs to make it easy to hold the tool while it is in motion, as shown in Fig. 4.

An Epiphan Pearl [10] device can be used to record the motion data of the MTMs and PSMs of the da Vinci in a synchronous fashion and a Python script can be used to playback the recorded motions. Due to time constraints, we were not able to use these tools in our system. Instead, we emulated the same functionality by asking an experienced user to teleoperate the PSMs from the surgical console using the MTMs when needed throughout the user study.

An inanimate task was used during the user study. The task setup, shown in Fig. 5, was placed inside the box trainer. The participants of our study could only see the task through the dedicated monitor. The task objective was to touch a number of pins in a predefined sequence. The sequence and number of pins was changed in different stages of the user study. The user study participants were asked to touch the top of the pins only with the bottom of the tool tip. They were instructed to do the task as fast as they can with the least amount of errors. Throughout the user study, participants

Figure 4: A closer view of one of the da Vinci PSMs after attaching a handle to make it easier for a user to hold.

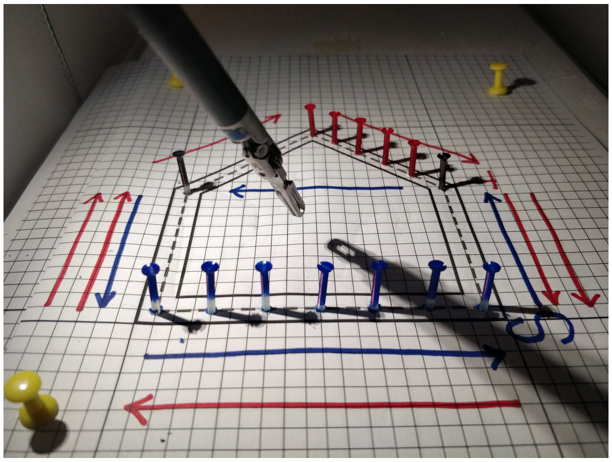

Figure 5: The task used in the user study was to touch the top of the pins with the end of the tool tip.

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

4.2 User Study

We recruited 21 participants from the University of British Columbia students who had no prior experience with robotic or laparoscopic surgery. We also asked an expert user to carry out the chosen task whenever needed in the study. In the ideal scenario, the robot's motion data should be recored during the task execution. Our ultimate goal was to see if training using one of the da Vinci PSMs would result in improving the trainees' performance while using the traditional laparoscopic tool.

At the beginning, 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 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 done 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), 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 doing the training task six times) before the evaluation phase.
2. Playback Group: This group learned via the hand-over-hand approach. In the ideal case, in this approach the robot should play back the PSM movement that was recorded during the expert's execution of the task. In our user study, we simulated the same effect by asking an experienced da Vinci user to teleoperate the PSMs from the surgeon's console. 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.

After the training, all participants performed two test trials on the same task, to evaluate the training outcome. The first trial was using the da Vinci robot arm to measure the amount of 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 what the participants learned using the da Vinci arm was transferable to the traditional laparoscopic tool.

The participants were also asked to do 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 *test task*. Again, one of these trials was done using the da Vinci PSM and the other was done using the traditional laparoscopic tool.

For some participants, parts of the collected data were corrupted and hence, we excluded their data. As a result, we have a total of 17 participants as follows: seven participants in the Discovery group, six in the Playback group and four in the DisPlay group. In the coming sections we present the results of these 17 participants only.

4.3 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 practical applications in surgery. In our study, the trainee should aim to execute the task in the shortest time with the lowest 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 [16]. The lower the value of this metric, the better.

Using the above metrics, we compared between the baseline performance and the performance in the evaluation phase on the training task within each of the three training groups (Discovery, Playback and DisPlay). We did this to check the performance improvements using the da Vinci PSM and the traditional laparoscopic tool separately. We also compared between the performance of the three groups in carrying out the test task.

5 RESULTS AND DISCUSSION

5.1 Results of the Training Task

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.

We first report the results of comparing the performance before and after training on the modified interface only. The DisPlay group showed the best performance improvement in terms of number of errors as shown in Fig. 6 with 75% decrease in the number of errors for the majority of this group (75% of the participants). A similar trend can be seen based on the the total number of errors multiplied by the completion time metric as shown in Fig. 7. The Display group again showed the best improvement by around 84% decrease compared with 56% and 34% decrease in the Discovery and Playback groups, respectively. Using the same performance metric, we also noted the general trend of performance improvement within the training trials for the Discovery and Display groups as shown in Fig. 8 and Fig. 9, respectively. For this latter group, these improvements may indicate the potential benefits of having playback training trials in-between discovery training ones.

When it comes to the improvement of the performance on the the traditional laparoscopic tool, we compared between the groups' performances before and after training again, but this time we were interested in the tasks performed using this tool only. As seen in Fig. 10, the majority of the Discovery group was the best based on the improvement in terms of completion time, with a decrease of around 43%. The majority of Playback and Discovery groups showed comparable decrease in the completion time by around 30% and 28%, respectively. On the other hand, these two groups show improvements in terms of number of errors, while the Discovery group's performance reduced after training. Fig. 11 shows that the majority of the DisPlay group made 17% less errors after training and the Playback group made around 11% less errors.

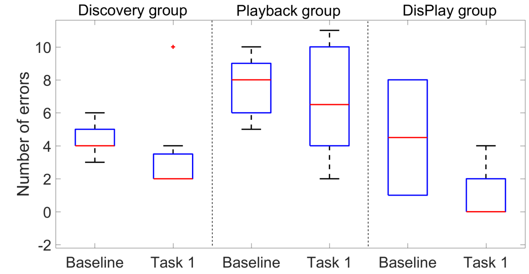

Figure 6: The improvement of the performance before and after training on the modified PSM in terms of the total number of errors.

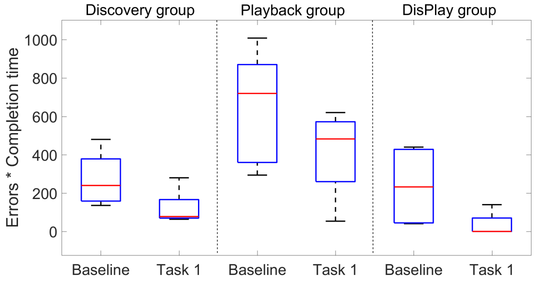

Figure 7: The improvement of the performance before and after training on the modified PSM in terms of the total number of errors multiplied by the completion time.

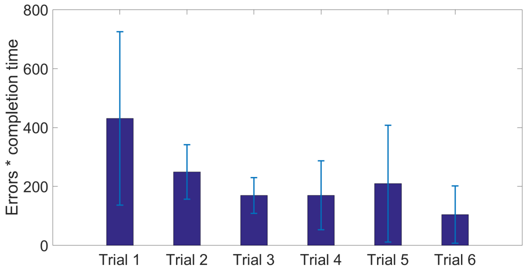

Figure 8: The learning curve of the Discovery group throughout the training trials on the modified PSM in terms of the total number of errors multiplied by the completion time.

We perform hypothesis testing using a T-test to verify that the results before and after training in terms of number of errors and completion time are significantly different for all the three groups. The test shows that for the Playback and DisPlay groups, the results are significantly different ($P < 0.05$). This is not the case with the Discovery group whose P is 0.052 for the errors results and 0.06 for the completion time results.

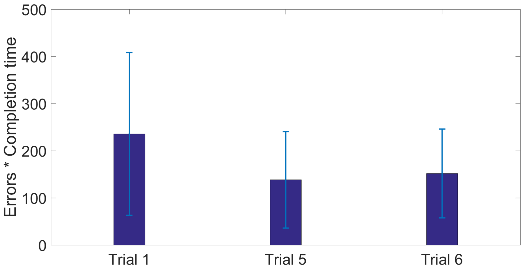

Figure 9: The learning curve of the DisPlay group throughout the training trials on the modified PSM in terms of the total number of errors multiplied by the completion time before and after the playback trials.

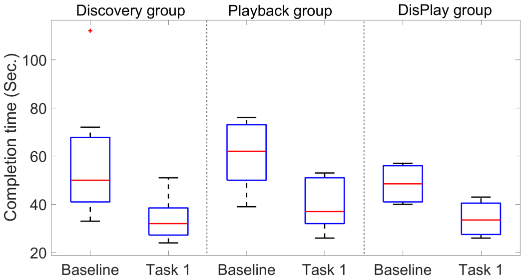

Figure 10: The improvement of the performance before and after training on the traditional laparoscopic tool in terms of the completion time.

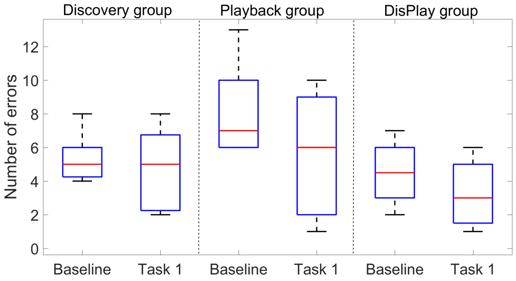

Figure 11: The improvement of the performance before and after training on the traditional laparoscopic tool in terms of number of errors.

5.2 Results of the Test Task

The last part of our user study was to test the transferability of the acquired skills during the training process. That is why we asked the participants to perform a test task two times, one using the modified PSM and the other using the traditional laparoscopic tool. This test task was similar to the training task with a couple of variations in the number and positions of the pins.

Using the modified PSM, the three groups showed comparable performance in terms of the multiplication of the time and errors, with the DisPlay group showing a slightly better performance as shown in Fig. 12. Using the traditional laparoscopic tool though, the DisPlay group showed the best performance compared with the other two groups as shown in Fig. 13.

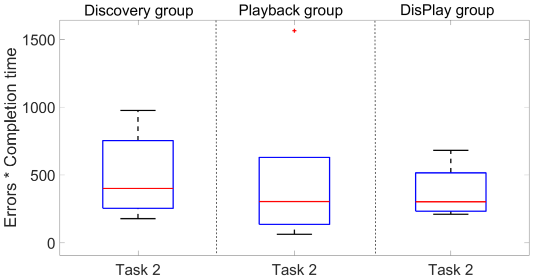

Figure 12: The performance of the three groups on the test task task using the modified PSM in terms of the total number of errors multiplied by the completion time.

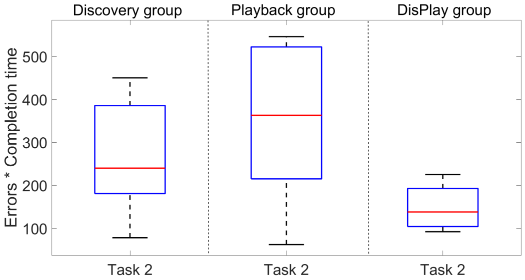

Figure 13: The performance of the three groups on the test task task using the traditional laparoscopic tool in terms of the total number of errors multiplied by the completion time.

5.3 Discussion

The large performance improvements of the DisPlay group compared with the other two groups in this small number of training trials refer to the benefits of combining both the discovery and playback training in learning motor skill tasks. Using discovery training only may require larger training time for the trainees to learn the "secrets" of doing the task faster, with less errors. These "secrets" include how to approach a pin gently and how to coordinate the tool movements so that it does not obscure the camera views.

On the other hand, by just following an expert's movements, trainees may not achieve their full potential. This is because the kinematics of each trainee do not necessarily be the same as the kinematics of the expert. In addition, there may be different ways of carrying out the same task efficiently. Furthermore, by doing playback training only, the trainees may not be able to generalize their training to different tasks. They may fall in the trap of memorizing and adjusting their performance only for the training task. They can overcome this only when they are given the opportunity to discover their own skills along with learning from the expert's trajectories as the case in the DisPlay group.

We provided a questionnaire form asking the participants to evaluate their training method on a scale of 5, with 1 being the worst and 5 being the best. All the Display group participants gave a score of 4 or 5 when asked about the learnability of used training. For the same item, 86% of the playback group and only 43% of the discovery group gave the same score. In terms of subject sanctification, all the display group participants rated their training method as 4 or 5 compared with around 71% of both the playback and discovery groups who gave similar scores. These subjective results showed the acceptance of the display training technique among the user study participants.

6 CONCLUSION AND FUTURE WORK

In this paper, we proposed the addition of record and playback buttons to the current interface of surgical robots. We showed how these new buttons enable two novel interactions with such systems, namely training for surgical robotics and training for standard laparoscopic surgery on the same surgical platform. We conducted a user study to evaluate the effectiveness of the latter interaction. The results from this user study show that adding these two buttons has the potential to improve the motor skills of novice users performing surgical training tasks. The results showed that a combination of discovery and playback training leads better performance with the least amount of errors. Moreover, this combination showed the best performance when it comes to the transferability of the acquired skill when testing on another task.

We believe that the results of this paper 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. 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 effective. Furthermore, it would be interesting to explore ways to record and playback specific important movements like pinching of the surgical instrument which we could not collect using the current system. 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 like the proposed one in this paper augment the increasing interest in using systems like the da Vinci Surgical robot as a platform for neuroscience researchers to study surgeons' motions in real life scenarios [12].

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