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Designing an Active Motor Skill Learning Platform with a Robot-Assisted Laparoscopic Trainer

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Abstract—**Laparoscopic Surgery poses significant complexity in hand-eye coordination to the surgeon. In order to improve their proficiency beyond the limited exposure in the operating theatre, surgeons need to practice on laparoscopic trainers. We have constructed a robotic laparoscopic trainer with identical degrees of freedom and range of motion as a conventional laparoscopic instrument. We hypothesize that active robotic assistance through a laparoscopic trainer improves training efficacy as compared to autonomous practice. In order to test the hypothesis, we have divided the subjects into two groups. The control group practiced on two laparoscopic tasks manually without feedback or supervision. The other group practiced on the same tasks with robotic assistance. Results from the robot-assisted group show that tool orientation (pitch and yaw joint motion) in the pointing task improved by more than 15%.**

I. INTRODUCTION

LAPAROSCOPIC surgery has become a common preference as the main treatment approach for many types of surgeries due to its numerous benefits to the patient [1]-[4]. However, laparoscopic surgery imposes demanding visual and physical conditions onto the surgeon as well [5], [6]. These factors suggest that laparoscopic surgery has a steep learning curve. Furthermore, live laparoscopic learning opportunities are limited and expensive. Studies have shown that improvement through simulated laparoscopic training does get transferred to the technical performance of laparoscopic procedures in the operating theatre [7]. It has also been suggested that trainees focus their attention on acquiring basic technical skills before being able to fully appreciate the intricacies of a theatre environment during their early exposure to live operations [8]. These factors suggest that trainees should master these basic technical skills outside of the operating theatre with laparoscopic trainers before being exposed to the delicate nature of live operations.

Current laparoscopic trainers range from physical box trainers [9] to virtual simulations [10]. Although there are many different advantages associated with the solutions available [11]-[13], none of them mimic the conventional hand-over-hand guidance that surgeons use to teach their juniors. Hence, in order to realize this function within a laparoscopic trainer, we have previously created a robotic laparoscopy platform which can record and replay reference training motions of laparoscopic instruments for the subject to mimic.

The notion of robotic assistance in motor training is not new. It has been widely researched as forms of stroke and geriatric rehabilitation to regain motor function where different methods of controlling the robot have been used such as in a tele-operated master/slave configuration [14], symmetric self-controlled manipulation for hemiplegics [15] and power assistive feedback control through localized EMG [16] and force sensors [17]. In contrast, robotic assistance for the honing of laparoscopic motor skill mastery, to our knowledge, has not been attempted before. In this paper, we shall explore the hypothesis that this novel way of training laparoscopic skills is more effective than the conventional unaided manner.

II. MATERIALS AND METHODS

A. Experimental Setup

The experimental setup comprises of the robotic laparoscopy trainer, a PC workstation that manages the robotic trainer as well as displaying the endoscopic viewpoint which is captured by a 720p HD webcam (Microsoft LifeCam HD-5000). The robotic laparoscopy trainer consists of a pair of surgical manipulators. Each surgical manipulator has five degrees of freedom (DOF), i.e. pitch, yaw, roll, translation (insertion / withdrawal) and tool tip activation, with similar range of motion in each DOF as a conventional laparoscopic instrument. A set of rotary encoders and DC motor actuators are employed on each axis to record and control the 3D motion of the surgical tool. The focus of the paper is on the robotic assistance for laparoscopic training hence it is independent of the detailed technical specifications of the robotic laparoscopy trainer.

B. Laparoscopic Tasks

In order to test the laparoscopic proficiency of the subjects, we have adapted two abstract laparoscopic tasks. The first task is a pattern tracing game where subjects are required to

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consistently follow the circular pattern, starting at the centre of the 9 cm diameter circle shown in figure 1, following the black line downwards and proceeding to trace the circumference of the red circle. With each revolution, subjects start and end at the centre of the circle and each trial consists of two revolutions. The circle tracing task requires the subjects to continuously manipulate orientation (pitch and yaw rotations) as well as approach (withdraw and insert) simultaneously to generate the planar circular motion as the circle is not positioned concentric with the laparoscopic tool.

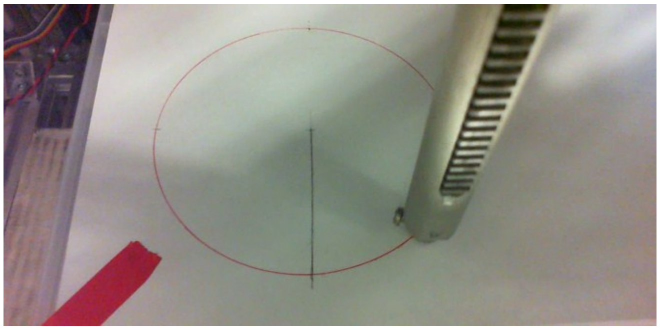

Figure 1. Subjects' endoscopic view of the circular tracing task.

The second task is a pointing game which is designed within a 3D maze of layered wires acting as vasculature that surgeons have to avoid in order not to accidentally cause hemorrhages. Subjects are required to point the tip of the laparoscopic instrument at the purple square boxes as shown in figure 2 by withdrawing, orientating and inserting the manipulator at correct orientations in order to reach through the 3D wire maze. For each trial, subjects start and end at the top right marker in a clockwise fashion.

Figure 2. Subjects' endoscopic view of the pointing task.

The two tasks are adapted from conventional basic laparoscopic training systems such as the Minimally Invasive Surgical Trainer – Virtual Reality (MIST-VR) [18], ProMIS surgical simulator [19] and Fundamentals of Laparoscopic Surgery (FLS) [20] that were designed to train and assess users on fundamental technical laparoscopic skills using partial laparoscopic tasks such as pick and placing, cutting a circular pattern and suturing. The circle tracing task is adapted from circular cutting pattern task found in FLS and ProMIS. The pointing task is adapted from the peg transfer/ pick & place task found in all 3 systems mentioned. Such partial task trainers focus on technical skills and do not replicate full procedures such as a laparoscopic cholecystectomy. However, the transferability of technical skill learnt from these laparoscopic trainer systems into clinical performance have been widely studied and validated [21].

C. *Experimental Protocol*

Twelve volunteers with ages between 21 and 32 (average age 27 years) from non-medical backgrounds volunteered for this experiment. The experimental procedure was conducted in accordance with the ethical principles for research involving human subjects in the Declaration of Helsinki. None of the volunteers had any prior training with laparoscopic instruments. All subjects performed the experiment with only their dominant hand. The subjects were assigned into two equal groups. One control group practiced on the two tasks autonomously with actuators turned off whereas the other group practiced on the same two tasks with robotic assistance. With respect to this paper, we shall define active training as training with robotic assistance and passive training as unaided autonomous training. Robotic assistance is rendered by fully controlling the subject's manipulator to move along a prerecorded reference trajectory. We rationalize that hand-over-hand guidance in conventional surgical tutelage starts by fully controlling the motions of novice apprentices. For each task, the subjects recorded an initial baseline assessment and proceeded with their group's allocated manner of practice. After 5 rounds of practice, a final assessment was taken. To reduce the effect of familiarization, the order of tasks was alternated with consecutive subjects.

Ideally, for simple tasks, the reference trajectories could be mathematically derived for the most efficient path but there were issues compensating for the anisotropic mechanical backlash in the system so we had to iteratively record a manually compensated trajectory by directly viewing and manipulating the tooltip with our hands akin to performing as an open surgery procedure. As future work, we intend to incorporate visual feedback error control to the robotic system to better compensate for the backlash. Also, we intend to implement more complex multimodal surgical scenarios in the future and record the optimal reference trajectories with experienced senior surgeons instead.

III. RESULTS & DISCUSSIONS

All statistical comparisons were analyzed using an analysis of variance (ANOVA) with statistical significance set at 0.05.

A. *Circular Tracing Task*

Figure 3 shows the three dimensional plots of the attempted circular path by the subjects in the active training group. Among the four assessed, only one did not show improvement after the training as seen in figure 3(d). Ideally, due to the planar objective, the tracing motion recorded should be planar as well (as shown in figure 3(a)). However, some subjects were observed to project a skewed or elevated plane of motion as shown in figures 3(b) and 3(c). These results highlight the problem of depth perception in laparoscopy. The partially skewed plane of motion in figure 3(b) reflects the reduced depth perception of regions further away from the perspective of the canted endoscopic view.

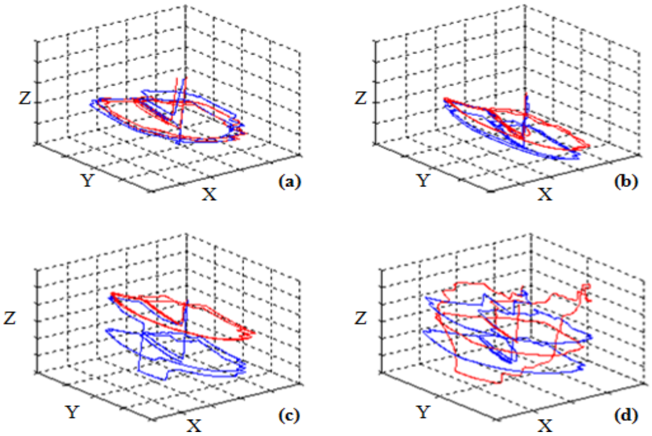

Figure 3. Examples of 3D paths in tracing a 9 cm diameter circle taken by (a) subject 11. (b) subject 12 with a partially skewed plane. (c) subject 9 with fully elevated path. (d) subject 7 with poor performance before and after robot assisted laparoscopic training. The blue line represents the baseline assessment and the red line represents the final assessment.

This leads to a conundrum in analyzing their data as, in the eyes of the subject, the endoscopic perspective showing their motions seemed to be on target but their tooltip was actually floating on a separate plane, albeit with well circular motions within that plane. Extrapolating the trajectory of the tooltip onto the real task plane will also amplify their motions (and associated deviations). In addition, analyzing the circular trajectory at the plane of motion captured will be hard to compare as the size of the circle for each subject will also be different and elliptical. As such, we could only do quantitative analysis for four out of the six subjects (subjects 7, 9, 11, 12) in the active training group who performed the tracing relatively close to the real task plane. Nevertheless, results from the four subjects show that the cumulative deviation of the tool tip from the circumference of the circular path reduced by 8.5% (p=0.11), suggesting improvement in consistency after the active training. Whereas the passively trained group showed an increase of 29.7% (p=0.89) in their path deviation.

B. Pointing Task

Efficiency in the execution of a given path can be inferred from the cumulative motion of each subject in completing the pointing task. The data was analyzed in the task space domain defined by three relevant DOFs namely the yaw, pitch and approach of the laparoscopic tool simulator. The improvement in performance between the baseline assessment and the final assessment is charted in figures 4 and 5. The active training group showed overall reductions of joint displacements by 15.4% (p=0.04), 15.6% (p=0.22) and 2.74% (p=0.79) in yaw, pitch and approach respectively. The series of active training appears to have greater influence on the orientation dexterity (yaw and pitch rotation) of the subjects. This may also be due to the nature of the tasks used.

In the passive training group, the joint displacements were in fact larger. All the subjects in this group experienced a need to increase the motion in at least one degree of freedom. The mean percentage increase in joint displacements for this group is 3.0% (p=0.80), 3.4% (p=0.75) and 0.5% (p=0.96) for yaw, pitch and approach respectively. Half of the subjects (subjects 9, 10, 12) trained actively shows consistent reduction in all 3 axes. In contrast, there is no clear evidence to show that the subjects from the passively trained groups improved their motion efficiency except for subject 4 whose performance deteriorated in all 3 axes.

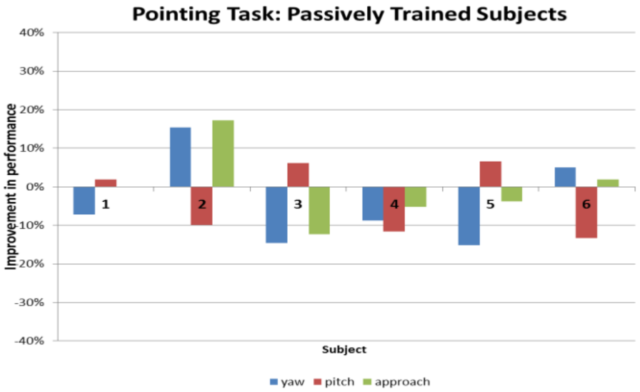

Figure 4. Percentile improvement in performance of the subjects in the passively trained group

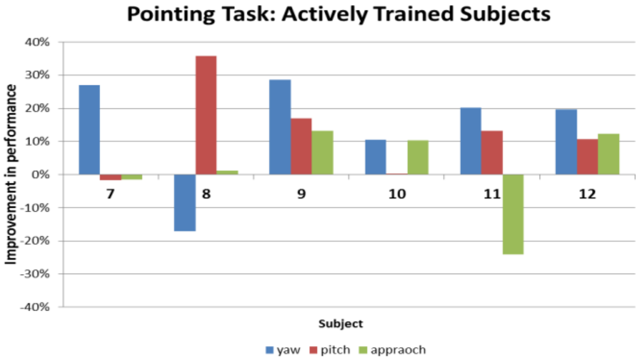

Figure 5. Percentile improvement in performance of the subjects in the actively trained group.

C. Timings

The time taken for the first and last assessment for all subjects and tasks are shown in Tables I and II. On average, when comparing the first to the last trial, subjects in the passive training group improved their timings by 21.8% (p=0.40) on the circle tracing task and 27.9% (p=0.30) on the pointing task, bringing the overall average to 24.8%. Whereas in the active training group, their timings improved by 2.2% (p=0.65) for the circle tracing task and 25.0% (p=0.08) for the pointing task, leading to an overall improvement of 13.6%. The timings from the final assessment for both tasks was not significantly different between the two groups (p=0.47 for circle task, p=0.64 for pointing task).

Timings have to be considered in conjunction with path efficiency in order to gauge subject performance as it indicates the level of confidence of the subjects. While there is improvement in average timings for both groups, it did not necessarily correlate with better motion efficiency and consistency as evident in the performance of subjects in the passive training group.

Table I: Time taken for circle tracing task (seconds)

Passive training group

Subject	1	2	3	4	5	6	Average
First Assessment	55.48	41.00	60.44	52.72	59.32	127.60	66.09
Last Assessment	38.96	23.88	47.84	50.24	53.08	97.76	51.96
Percentage change (%)	29.78	41.76	20.85	4.70	10.52	23.39	21.83

Active training group

Subject	7	8*	9	10*	11	12	Average
First Assessment	100.72	73.16	68.16	33.16	56.84	66.88	66.49
Last Assessment	92.68	52.84	55.96	52.76	47.48	65.44	61.19
Percentage change (%)	7.98	27.77	17.90	-59.11	16.47	2.15	2.19

* indicates subjects whose path trajectories were omitted from analysis.

Table II: Time taken for pointing task (seconds)

Passive training group

Subject	1	2	3	4	5	6	Average
First Assessment	53.60	48.80	56.80	89.68	42.40	292.76	97.34
Last Assessment	43.44	26.92	40.68	62.56	53.04	88.32	52.49
Percentage change (%)	18.96	44.84	28.38	30.24	-25.09	69.83	27.86

Active training group

Subject	7	8	9	10	11	12	Average
First Assessment	119.48	67.96	67.60	51.72	85.32	76.60	78.11
Last Assessment	71.64	72.72	54.72	37.60	42.92	60.56	56.69
Percentage change (%)	40.04	-7.01	19.05	27.30	49.70	20.94	25.00

IV. CONCLUSION

As shown by the favorable results for both tasks in the actively trained group over the passively trained group, the initial assessment of the concept of robotic assistance in laparoscopic motor skill learning is promising.

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