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Development of a Low-Cost System for Laparoscopic Skills Training

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Development of a Low-Cost System for Laparoscopic Skills Training

A thesis submitted in partial satisfaction of the
requirements for the degree of Master of Science

in

Engineering Sciences (Mechanical Engineering)

by

Jui-Te Lin

Committee in charge:

Professor Tania Morimoto, Chair
Professor Nicholas Gravish
Professor Michael Tolley

2020

The Thesis of Jui-Te Lin is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California San Diego

2020

DEDICATION

For my parents and the whole family.

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ABSTRACT OF THE THESIS

Development of a Low-Cost System for Laparoscopic Skills Training

by

Jui-Te Lin

Master of Science in Engineering Sciences (Mechanical Engineering)

University of California San Diego, 2020

Professor Tania Morimoto, Chair

Technological advancements in video equipment and biocompatible materials has enabled improvements in complex surgery through small incisions. The mastery of these laparoscopic surgical techniques is now a requirement for surgeons, however, the necessary skills are not intuitive and require hundreds of practice hours. The current state of surgical education includes animate models, inanimate physical models, and computer-based simulations, the latter of which are limited by cost, accessibility, and a lack of engagement. We propose a novel low-cost training interface that mimics the laparoscopic surgical environment using customized instruments whose movement and control are used as inputs for video games. The system is significantly less expensive than commercial systems and allows users freedom to select and play any game, enabling a take-home system with potential for higher levels of engagement, as well as familiarity and expertise with ambidextrous laparoscopic hand motion. A preliminary study compared performance on FLS (Fundamentals of Laparoscopic Surgery) testing before and after training. For a precision cutting task, groups that trained on a standard simulator or on the new system with either a non-inverted or inverted hand-instrument mapping, showed statistically significant improvements, warranting further investigation of training with this new system.

Chapter 1

Introduction

There has been significant growth, development, and innovations in minimally invasive surgery (MIS) since the early 1980s. Minimally invasive surgery (MIS), in general, includes colonoscopy, laparoscopic, and endoscopic surgery. These types of surgeries involve a minimal access port through which the instruments and endoscope are inserted [24]. The first growth phase involved the development of novel surgical instruments, known as laparoscopic instruments [47]. These instruments, including auto-clip device and trocar-related device, were meant to improve the efficiency and the safety of laparoscopic surgery [6]. The second phase started in the mid-1990s to 2000, and was focused on expanding the practice of MIS [47]. In addition, the ideas of robotic surgery and image guidance techniques were first introduced to MIS [47]. As the demand for higher precision and accuracy in minimally invasive surgery has increased, the development of surgical robots has became a promising research area [12]. Robotic surgery leverages numerous complex engineering techniques. As a result, the need to continue research and development of surgical robotic technology lead to the third growth phase in the late 2000s.

Since the first laparoscopic cholecystectomy performed in 1985, laparoscopic surgery has revolutionized surgical procedures and technique [54, 30]. The number of minimally invasive, or laparoscopic, surgeries performed each year continues to rise and reached nearly 15 million cases worldwide in 2017 [1]. Compared to traditional open surgery, laparoscopic surgery offers a number of advantages, including an improved pain profile, shorter length of stay, and better aesthetics [2, 26]. More importantly, minimally invasive surgery is regarded as the greatest innovation in the surgery over the past 30 years [27].

These patient benefits, however, come at the cost of increased difficulty and high learning curves for surgical trainees, due to a number of factors. In particular, it can be difficult to learn how to perform a 3-D task using 2-D visualization, use non-wristed instruments, operate on a fulcrum, and operate with reduced haptic feedback [2, 41, 31, 25, 16]. General surgery residency training programs across the country continue to search for methods to speed up or reduce this learning curve in order to produce well trained laparoscopic surgeons [4, 50, 37]. As a result, many surgical educators have turned to surgical simulation to supplement clinical experience [43].

Consequently, researchers and companies have begun designing more advanced surgical simulators for training and have aimed to increase the accessibility of the simulators for medical students. Instead of practicing basic surgical skills in the operating room and with the actual tools, the simulators are able to mimic the virtual surgical environments, while also offering varying difficulty to the user. The development of such simulators has improved surgical training in many ways, including the ability to customize tasks, increase accessibility, and a reduction in material waste which occurs in the standard endotrainer, such as gauze in cutting, suture in knot tying, and nylon in ligating loops. However, the high cost of these training systems, along with the often tedious tasks, can deter adoption and wide-spread use. Therefore, there is a significant need to build a low-cost engaging training system to provide basic surgical training.

1.1 Robot-assisted surgery

Robot-assisted surgical systems have the potential to overcome some of the challenges associated with conventional minimally invasive surgery. Often these systems are teleoperated, allowing the surgeon to manipulate the robot while seated at a remote operating console [57]. The surgeon can operate through tiny incisions in the patient's body, controlling a camera, as well as surgical instruments. The surgeon console can often provide a high-definition 3-D view, leading to improved visualization compared to standard MIS [20]. In addition, the robotic device, which can have greater dexterity and a larger range of motion than a human, enables the surgeon to perform challenging tasks more efficiently and accurately. In 1999, Intuitive Surgical Inc. launched one of the first robotic surgical systems, known as the da Vinci surgical system, to the world [45]. The initial system contained two robotic operating arms and one camera holder. Each of the robot arms can provide 7 degree of freedoms which is exactly the same with the human arm. It allows surgeons to perform various minimally invasive procedures with high precision and accuracy. There remain open challenges, including the high cost, reducing haptic sensations, and reducing the amount of required surgical training.

Studies in recent years have compared robotic surgery to traditional laparoscopic surgery. For instance, a study over a 13-year period found that there were no statistical differences in outcomes or length of hospital stay [23]. Another study showed the main difference between robotic and traditional surgery was that the cost was $2700 more per patient and required a longer surgical operating time [36]. As a result, many researchers strongly advocate extensive research to validate the effectiveness of robotic surgery before wide-spread adoption [55].

Figure 1.1. This figure, which originally appeared in HWR Schreuder et al. [44], shows the da Vinci S robotic system with a master console and a patient side robot arms(Intuitive Surgical, Inc.)

In addition to the development of conventional rigid link robots, there has been an increasing effort to create flexible robots capable of operating in clinical scenarios. The benefits of these flexible robots includes greater accessibility to confined and unstructured anatomy and the ability to miniaturize the robot body. Continuum robots in particular have an elastic structure and are beneficial for the minimally invasive surgery, which requires small, deformable, and narrow instruments [33]. Typical materials include springs, elastic tubes, and braided polymer tubes [8]. Today, many companies, including Intuitive surgical, Auris Health, Verb surgical, Stryker, and Medtronic, have been developing flexible robotic systems, aiming to build the next generation surgical robot [9].

1.2 Conventional laparoscopic surgery

Laparoscopic surgery is a technique of using only small incisions in the abdomen or pelvis. In this procedure, 5 - 10 mm diameter instruments can be introduced into the abdomen through trocars and the surgeon can then manipulate, cut, and sew the tissue. Common laparoscopic instruments include graspers, scissors, clip applier and electrodes [51]. Today, most of the advanced devices integrate multiple functionalities into a single laparoscopic instrument. For example, LigaSure retractable L-hook laparoscopic instrument from Medtronic provides the user five functions in one device. This device provides the ability of monopolar dissection, vessel sealing, grasping, cutting, and blunt dissection. The benefits of this type of advanced device are that the surgeons are not required to switch between several different instruments during the surgery. The device could potentially lower the complexity and improve the operating time.

Figure 1.2. This figure, which originally appeared in Medtronic et al. [34], shows the five functionalities/ inputs featuring on the LigaSure retractable L-hook laparoscopic instrument

Conventional laparoscopic surgery has dominated the surgical paradigm for several decades [52], and its impact has been well documented through feedback from surgeons and patients. Further, the laparoscopic training curriculum has been well established and has been proven to be useful and applicable for surgery. These reasons could help explain the widespread use of conventional laparoscopic surgery today. Compared to robot-assisted surgery, conventional surgery is more affordable, well-defined and well-studied. However, the loss of 3D visualization, the fulcrum effect, and high complexity could still make it challenging to perform.

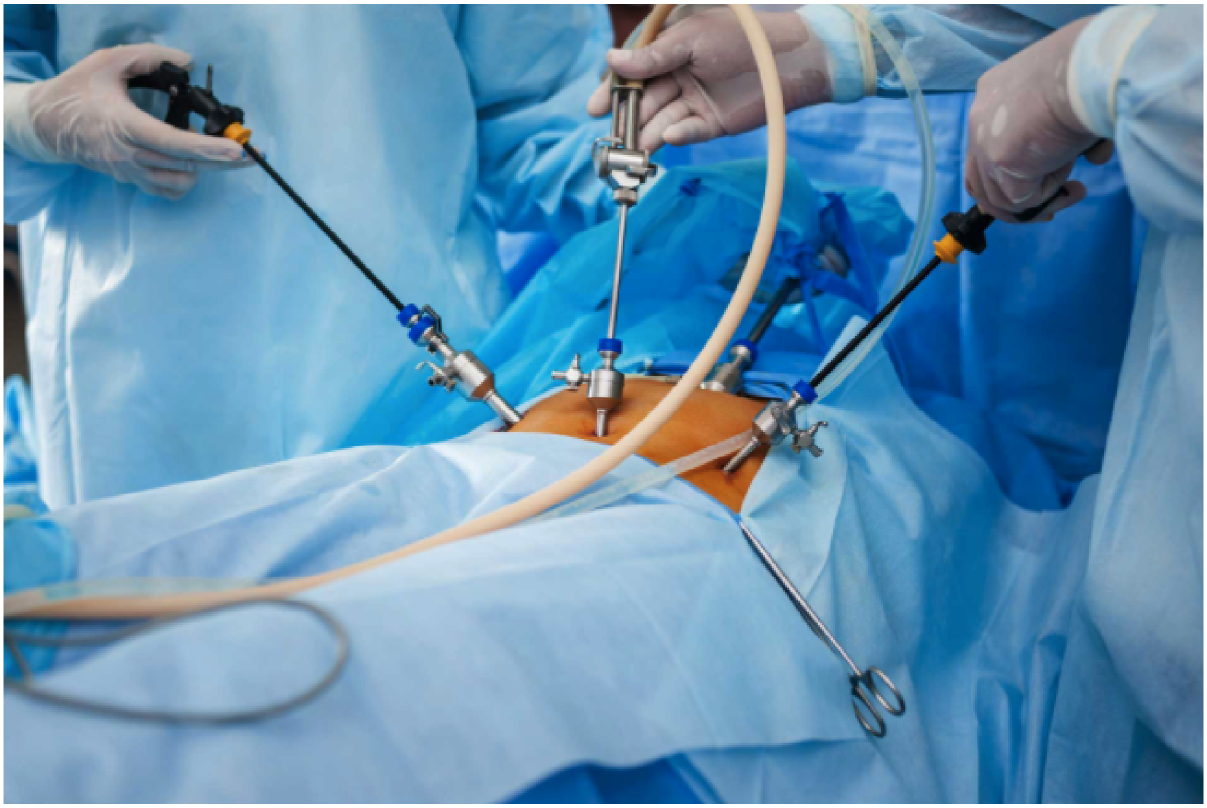

Figure 1.3. This figure, which originally appeared in Daily News et al. [38], shows the surgeons are performing the laparoscopic surgery.

1.3 Training for laparoscopic surgery

There are a number of different models used for laparoscopic skills training. On-the-job training, including performing surgery on patients, provides trainees with the most realistic experience. However, there are ethical and logistical complications when trainees are allowed to“practice” on real patients. Commonly, animate models are used to protect patient safety. These models include human cadavers and live animals, which also provide high-fidelity simulations of real life procedures. However, their high cost and limited availability make animate models less attractive options for most training programs [39].

Inanimate models, or simulators, on the other hand, are reusable, safe, and generally more cost effective. To-date, numerous different simulators, both commercial and non-commercial, have been developed for training and performance evaluation [28, 32]. These simulators can be roughly divided into two groups. The first group, box endotrainers, consists of a training box with multiple ports for inserting instruments that physically interact with real life objects, such as pegs, suturing pads, needles, or animal tissue. This type of trainer features a digital camera mounted over the operative field to allow basic laparoscopic skills training, including tissue handling and suturing [28, 22]. The second group of trainers are computer-based simulators. These trainers use controllers that do not physically interact with objects, but rather act as joystick-like handles to project user input into a virtually simulated environment. Here the surgical trainee can practice tasks such as suturing, knot tying, and tissue ligation. These systems will often try to provide some form of haptic feedback to enhance the simulated experience as well [15, 49].

Table 1.1. Comparison of laparoscopic training systems

System	Price (US$)	Tasks/Games
Proposed system*	**200**	**any Xbox 360 game**
3-dMed trainer	400-3000	basic tool handling tasks
LapTrainerTM	1250 [48]	basic tool handling tasks
Pyxus Pro Move	2500 [53]	basic tool handling tasks
FLS Trainer	3528 [29]	basic laparoscopic standardized testing
ABC-lap trainer	4316 [14]	basic tool handling tasks
LapSim VR	55000	VR simulated surgery case[3]

*System proposed here, including cost of Xbox 360 console

Despite the large number of simulators on the market, wide-spread adoption has been disappointingly low due to several factors. First, as seen in Table 1.1, most commercial simulators cost several thousands of dollars, making it difficult for many training programs to purchase systems [13]. Second, even when programs do have these simulators available for trainees, the usage time tends to be low. The low number of practice hours could be, in part, due to low fidelity or non-goal oriented training causing a lack of engagement and motivation [19]. Finally, because of limitations on the number of work hours of medical residents, there is a limited amount of time that they can spend training in simulation laboratories [7]. The development of lower-cost, engaging, portable systems could enable trainees to practice their skills at home, potentially leading to more training hours, and in turn, improvements in basic laparoscopic skills.

1.4 Basic skills and correlation with video gaming

There are a number of unique basic skills required to perform laparoscopic surgery, compared to traditional open surgery [18]. In particular, these skills include hand-eye coordination, fine motor control, reaction time, ambidexterity, and spatial awareness [40, 56, 25]. For example, to successfully perform laparoscopic procedures, one must develop an understanding of spatial relationships as well as psychomotor skills. These skills are critical for proficient manipulation of surgical instruments in a 3-D operating field, while only viewing the instrument motion on a 2-D video screen [40]. The challenge of learning to be ambidextrous in order to operate an instrument in each hand, with the added constraint of operating in a confined space, also increases the learning curve. Finally, by operating through a port in the abdominal wall, there is a perceived inversion of movement between the instrument handles and the instrument tip, called the "fulcrum effect", which requires significant practice to acquire proficiency [10, 17].

These basic skills are critical for successful surgical training, prompting researchers to investigate how various methods, tasks, and activities may relate to improving these skills. In particular, a number of recent studies have shown that a few skills important for performing laparoscopic surgery, may correlate to skills that can be acquired from playing video games [46, 31, 11]. For example, video gaming may help refine generic visual skills, including the ability to focus on a particular task, while still taking in peripheral details [31]. Video gaming also helps improve hand-eye coordination. While no single study was able to show that practicing these games would improve surgical skills, they did find that this experience could be used as a predictor of inherent laparoscopic skill [41]. Another study found that residents and attending physicians who self-reported playing video games for over three hours per week in the past, performed the Rosser Top Gun Laparoscopic Skills Program (Top Gun) 27% faster and with 37% fewer errors than those who had never played [11, 42].

These initial studies have prompted further investigation into the role of video gaming on training basic laparoscopic skills and the development of new training interfaces. The Wii-Underground, for example, is a video game based simulator developed by Nintendo. Their custom game, "Underground", can be played using a controller that mimics a laparoscopic instrument [7]. Validation of this system demonstrated a correlation between the amount of time spent using the system and performance on a basic skills task [21]. However, a transfer of skills from the Underground system to a Fundamentals of Laparoscopic Surgery simulator and subsequently to the operating room has yet to be established, and the system was limited to playing only the customized game. Finally, there has been no work, to our knowledge, that has investigated the effects of using an inverted mapping inherent in laparoscopic surgery in conjunction with off-the-shelf games.

1.5 Contributions

Our contributions are as follows. (1) We present a novel low-cost training interface that does not require specialized software. The interface mimics a laparoscopic training box with standard instrument handles that function as video game controllers (Fig. 2.1). These features are important for mainstream adoption, since the low-cost would allow the system to become a take-home setup, and the ability for users to select and play games of their choice could help enhance motivation and engagement. The system combines the cognitive and mental aspects of playing a spatial game, with the physical muscle memory required for laparoscopic surgery. (2) We present preliminary data showing the potential of the new system to help with training basic skills needed to perform simple laparoscopic surgical tasks. These results lay the groundwork for future long-term and large-scale studies to evaluate the full extent of the system's potential for laparoscopic training.

Chapter 2

System design

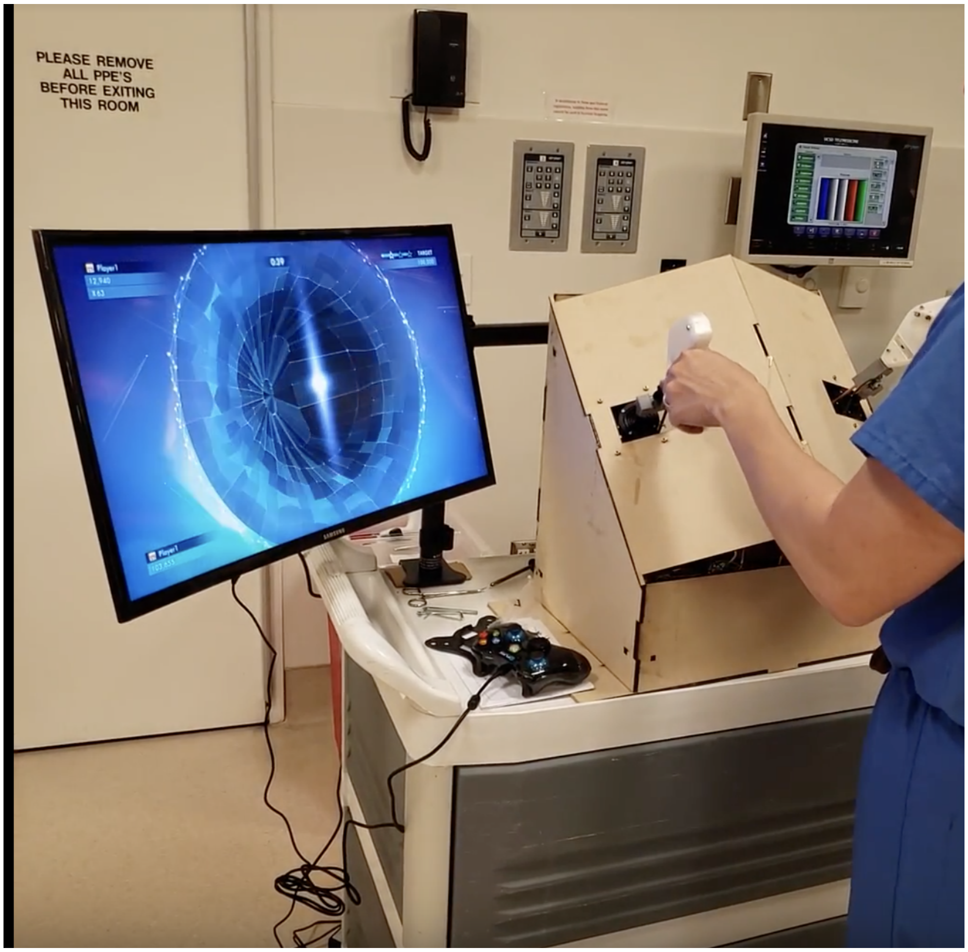

Figure 2.1. Overall system includes a training box with two instruments whose movement and inputs map to controls for a video game, displayed on an external monitor.

The structure and overall feel of the new training system is designed to mimic a standard laparoscopic training box,consisting of two instruments inserted through ports in the box. However, rather than performing a physical training task, movement of the instruments are mapped to controls for a video game console, enabling users to train by playing the game of their choice. The control inputs from each controller map to a PCB from an Xbox 360 controller mounted inside the box. An overall system diagram is shown in Fig. 2, and this section describes the mechanical and electrical design of the new laparoscopic training system.

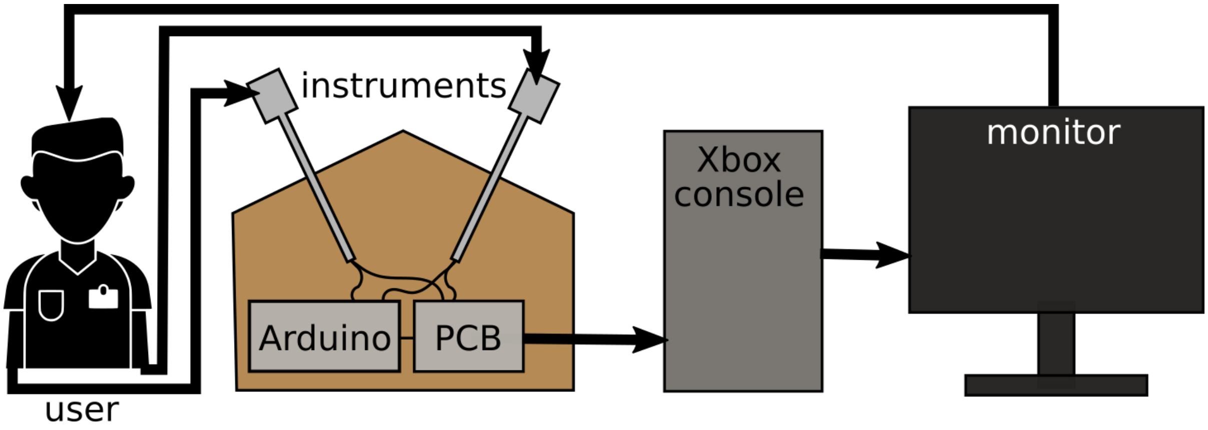

Figure 2.2. System diagram illustrating how the user moves the instruments, which are wired to the controller PCBs. These inputs are fed into the Xbox console and displayed on a monitor. The user then uses this visual feedback to control the instruments.

2.1 Training box design

The training box itself is designed much like standard box-trainers, which are made to mimic a laparoscopic environment. Most box-trainers are made of acrylic, or a similar plastic, and are sometimes made of metal [49]. Due to our goal of developing a low-cost, yet durable system, we selected to use medium-density fiberboard as the main material. It is strong enough to prevent damage from users, even during more vigorous use, and it is easy to cut and assemble. The critical dimensions of the training box, including the distance between the ports and the angle of the top surface, are shown in Fig. 2.3. To ensure the proper height for each user, an adjustable table or a step stool is used. The training box has two port locations through which the instruments, described in the subsequent section, are inserted.

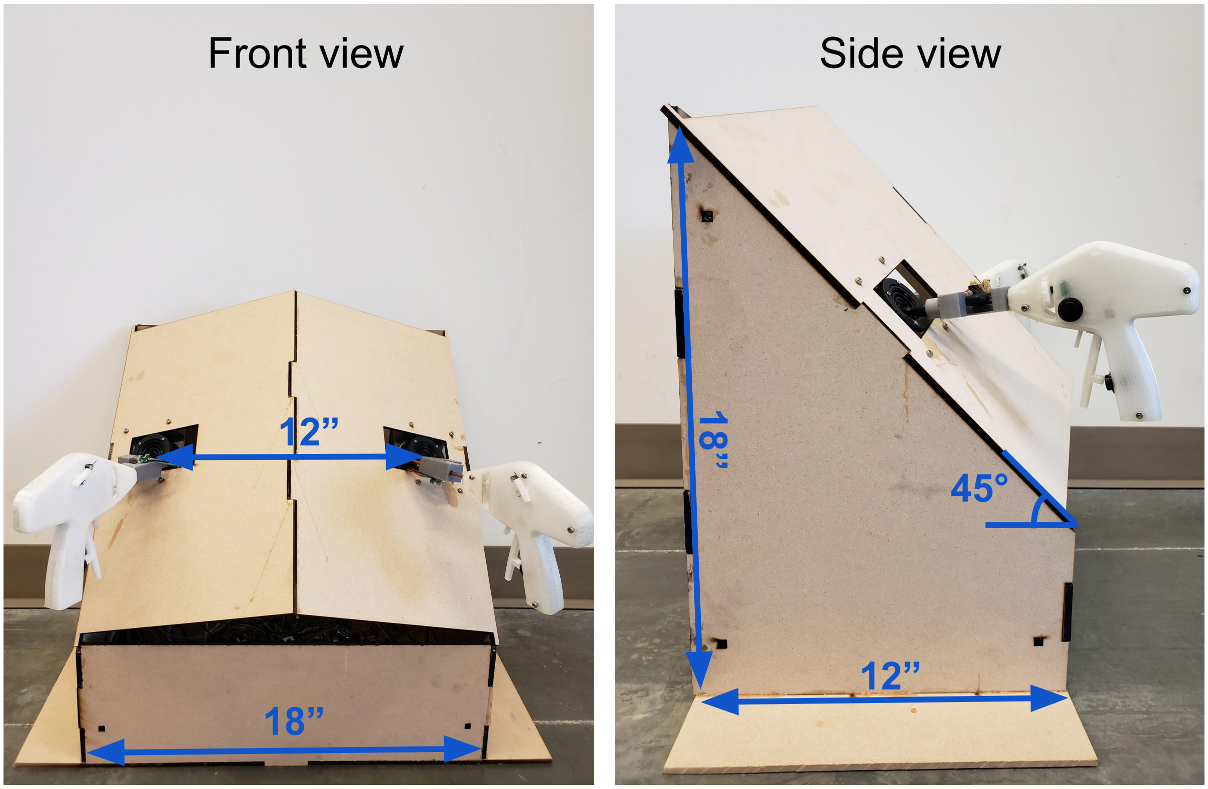

Figure 2.3. Front and side views of the training box and associated dimensions.

2.2 Instrument design

There are a number of laparoscopic surgical instruments available on the market. Each has its own design, however, the functionality and general structure remain relatively consistent [5]. For this study, the Ligasure Retractable L-hook Laparoscopic Instrument from Medtronic (shown in Fig. 2.4) was used as a reference for the design. The instruments for the new system were 3-D printed with PLA (polylactic acid) using an Ultimaker 3, with overall dimensions of approximately 140 x 141 x 24 mm and a shaft length of 245 mm. The Medtronic instrument consists of five inputs, including a scroll wheel, a button and three triggers. Based on feedback from clinicians at the University of California, San Diego, four inputs were identified as being critical for most procedures, and mechanisms with appropriate sensors were designed to enable the measurement of each.

First, we designed a mechanism to match the feel of the triggers, by mounting torsion springs inside the instrument. When the user presses the trigger, the torsion spring is twisted, causing it to exert a torque similar to the triggers found on standard instruments. Trigger presses are detected via a button press that occurs as the trigger reaches the end of its stroke length. Second, we designed a wheel, that could attach directly to the shaft of a 12 mm rotary encoder (Mouser Electronics) in order to detect any changes in rotational position. And finally, we added a push-button on the face to match that on the Medtronic instrument. It should be noted that the two instruments both consist of the same input mechanisms, however, they are mirror images of one another and are therefore specific to either the left or right hand.

In order to use the instruments to control the movement inside a video game, it is critical to be able to track the x, y, and z positions of the instrument shafts. To measure the x and y position of each instrument, a 2-axis arcade joystick (ServoCity R-204) is used. These joysticks are capable of 100°of tilt about both axes, and have an internal spring that centers them back to the neutral position. They are built to be highly robust, for arcade games, and their output can be directly mapped to movement of a joystick found on a standard video game controller. The arcade joysticks were mounted to the top plate of the training box, and the shaft of the joystick was connected to the instrument shaft via a 3-D printed mount, as shown in Fig. 2.5.

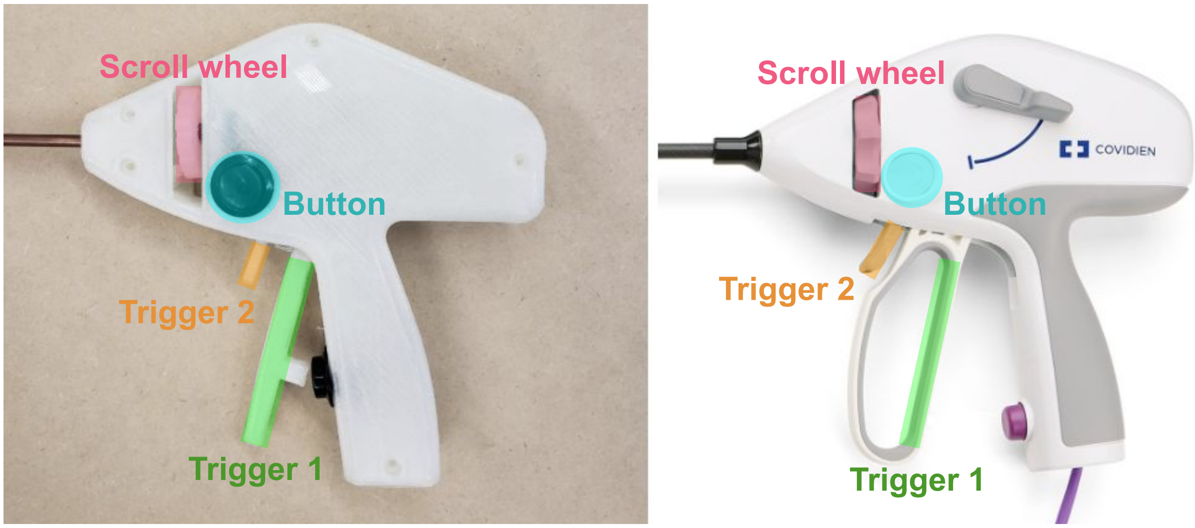

Figure 2.4. Customized instrument for the new system (left) and inputs corresponding to critical inputs on a commercial instrument (right).

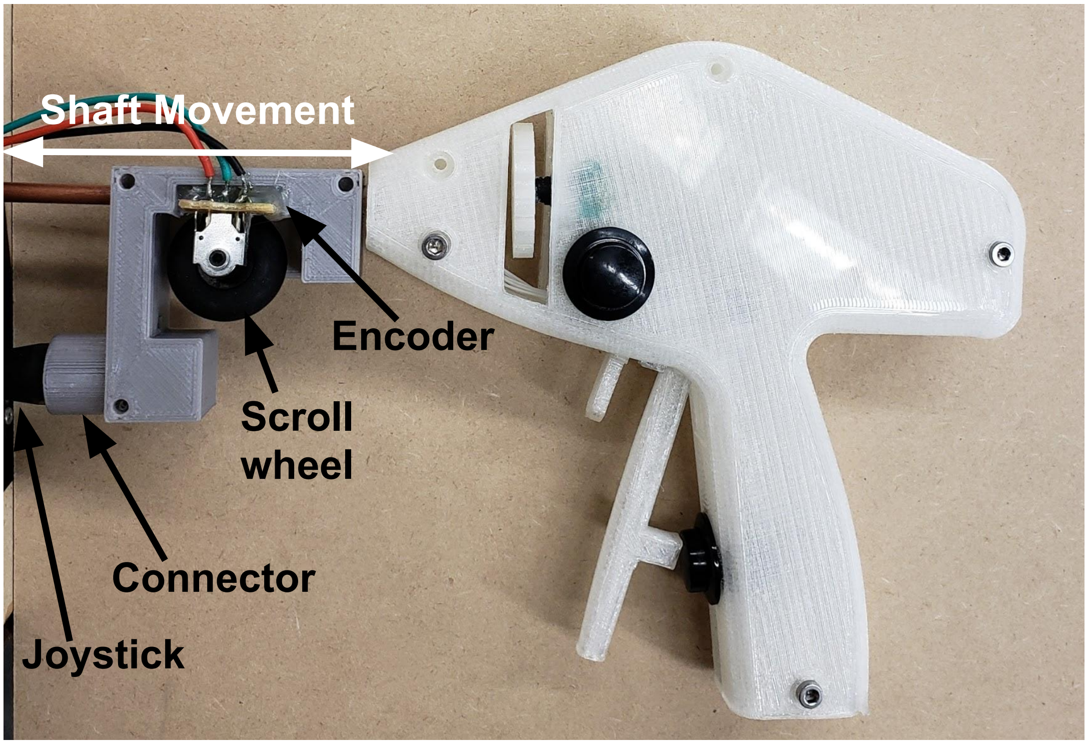

Figure 2.5. Close-up view of the module housing the scroll wheel and rotary encoder used to measure the z position of the instrument. The module connects directly to the joystick used to measure the instrument's x and y positions.

To measure the z position of the instrument, a mouse scroll wheel and associated rotary encoder (Amazon Basics) are used (Fig. 2.5). The wheel rotates via a friction-drive mechanism, driven by the linear motion of the instrument shaft. The radius of the wheel is 12mm and the encoder has 24 pulses per revolution, resulting in a resolution of 3.14 mm along the z axis. As explained in Section 2.3, z-axis movement is currently being mapped to a digital button press, but could be used as an analog input in future versions. The wheel-encoder assembly is housed inside the same module that mounts to the joystick, together enabling the measurement of the x, y, and z position of the instruments in real time.

The final design feature of the instruments, is that the shaft is hollow in order to contain all the wires from the mounted sensors. Ensuring that no wires are exposed is important for the system to be able to withstand continual, and possibly vigorous use. The hollow shaft routes the wires from the body of the instrument down into the training box, where they are connected to the controller boards. Although the systems have not been explicitly fatigue tested, they have been successfully used for over 20 hours, without any signs of wear. The triggers in their current form are the most susceptible to wear over time due to their constant, and often vigorous, use, however, this potential issue could be easily addressed by using alternative materials and fabrication techniques for a commercial version.

2.3 Electronics and input mapping

In order to easily map instrument movements and inputs to controls for a video game, we used the PCB directly from a video game controller. In this version of the system, we selected to use the Xbox 360, primarily due to the large number and variety of games available and the relatively low cost. In addition to an Xbox 360 console and two controller boards, an Arduino Uno was used.

There are many different possible ways to map the inputs from each of the instruments to the inputs on the controller. The goal was to select a mapping that would force the user to practice the motions and inputs most common in laparoscopic surgeries, while at the same time, enabling intuitive game play. The mappings shown in Fig. 2.6 were those used for the current study, but they can easily be changed for future use depending on the games selected. The button, Trigger 1, and scroll wheel located on the instrument body are mapped to digital inputs on the video game controllers. These inputs are therefore directly wired to the appropriate location on the board. Trigger 2 is mapped to an analog input on the video game controller (back trigger). However, because Trigger 2 can only transmit two states– pressed or not pressed– the control of this input also becomes binary. An Arduino Uno is used to detect whether the trigger has been pressed, and if so, it generates the necessary Pulse Width Modulation (PWM) signal to control this back trigger at full throttle. Movement along the z axis is currently mapped to a digital button on the video game controller. When the instrument is pulled up past a given threshold, the corresponding button press will be triggered via a 2-channel relay module (SainSmart) controlled by the Arduino Uno.

The x and y movement of the instruments were mapped to the x and y movement of the joysticks on the controllers. As explained in Section 3, we tested two different variations of this mapping in order to determine

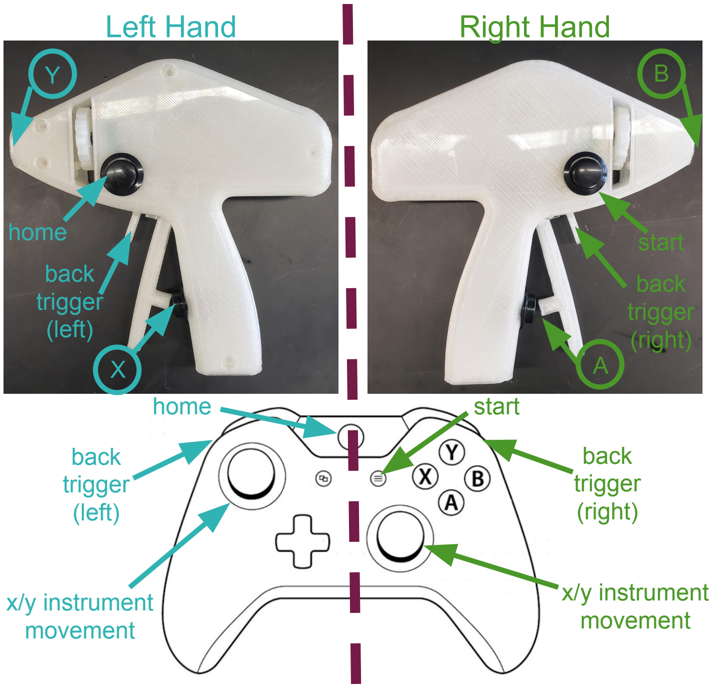

Figure 2.6. Input mappings from the customized instruments to a standard Xbox 360 controller. While these mappings were used for the current study, they can easily be changed for future use depending on the games selected.

whether one was more helpful in training skills needed for laparoscopic surgery. The first variation simply mapped the movement of the instrument handle, and therefore the user's hand, to movement in the video game. In other words, as the user moves his or her hand to the right, the cursor on the screen also moves to the right— exactly the same as moving the controller's joystick (Fig. 2.7a). The second variation was designed to mimic the rather non-intuitive mapping seen in laparoscopic surgery, known as the fulcrum effect, which leads to an inversion of movement between the instrument handle and instrument tip [2]. In other words, as the surgeon moves his or her hand to the right, the instrument tip moves to the left (Fig. 2.7b). For this second variation, which we have called the "inverted" mapping, the cursor on the screen therefore moves the same direction as the instrument tip, which is the opposite direction of the hand.

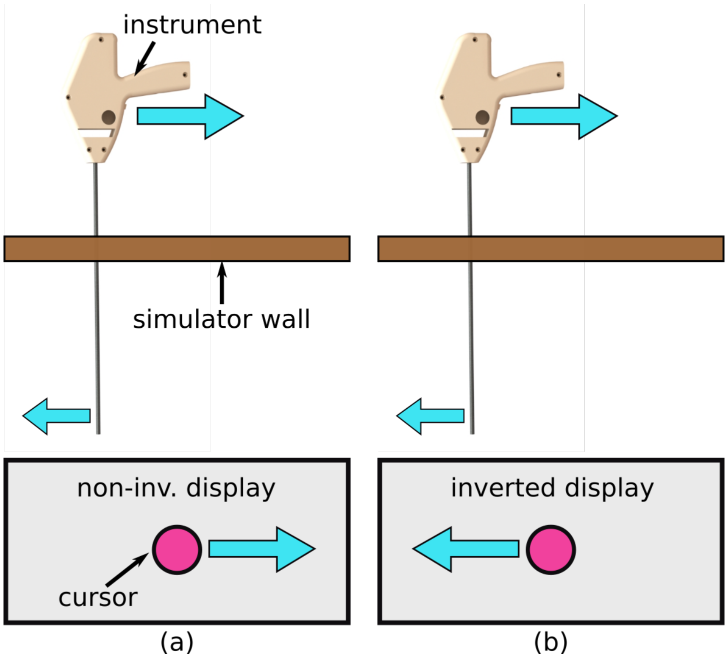

Figure 2.7. Two different methods were used to map the movement of the instruments to the movements of the cursor on the visual display. In the (a) non-inverted mapping the cursor moves in the same direction as the instrument, while in the (b) inverted mapping the cursor moves in the opposite direction, mimicking the fulcrum effect.

Chapter 3

Preliminary Study

In order to assess whether the new system can help improve basic laparoscopic skills, we performed a preliminary study with laparoscopic naive subjects. The goal was to collect initial data and feedback on the system's effectiveness for training, as well as its ability to engage and motivate users. In addition, the aim was to determine whether the new system has the potential to achieve comparable results to training on an existing commercial system.

3.1 Game selection

By design, the system enables the user to select and play any Xbox 360 game he or she would like. However, for the current study, we limited the game selection to three games (shown in Fig 3.1) in order to allow participants to focus on playing the games, rather than spending significant time switching or selecting which game to play, and in order to ensure that users played games that required both hands and a number of different inputs.

Game 1: *Geometry Wars 3* was selected in order to help train the use of both one's right and left hands. The right hand must be used to control the orientation of aiming and shooting, and the left hand must be used to move around the screen.

Game 2: *Sonic Sega All Star Racing* was chosen in order to help train motor control skills and hand-eye-coordination of the left hand (typically the non-dominant hand), which was used to drive the car. A combination of inputs from the left and right instruments were also used for speed control and tool selection.

Game 3: *Metal slug 3* was selected as a more challenging game and because of the general popularity of this genre. The left hand was again used for navigation, while the right was used to shoot and launch weapons.

(a) (b) (c)

Figure 3.1. Screen shots of the games selected for the preliminary study, including (a) Geometry Wars 3, (b) Sonic Sega All Star Racing, and (c) Metal Slug 3.

3.2 Study design

To assess the potential of our system to improve basic skills, we compared performance on a standard FLS (Fundamentals for Laparoscopic Surgery) Test for four groups of test subjects [35]. FLS is a testing modality approved by the American College of Surgeons to assess basic laparoscopic skills of surgeon trainees. In its entirety, it consists of five different tests— peg transfer, precision cutting, securing looped sutures, and two different suturing tasks. Each of these tests are designed to simulate a component of laparoscopic surgery and are organized in increasing level of difficulty. For this preliminary study, we chose the first two tests (Fig. 3.2) which used similar tools with relatively low degrees of complexity. The first test was the peg transfer test, which is considered the most basic of laparoscopic tasks. In this test, the subject is asked to transfer six silicone beads from one set of pegs to another, and then back. The second test was the precision cutting test, which requires a higher level of hand-eye coordination and familiarity with the instruments to accomplish. In this test, the subject is asked to cut an exact circle around a marked piece of gauze.

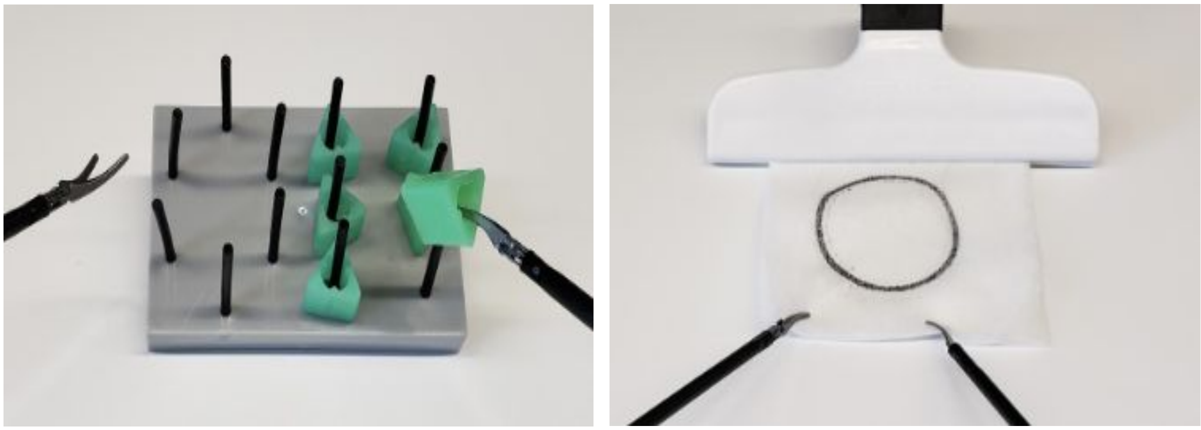

Figure 3.2. Two FLS tasks used for preliminary study. Peg transfer task (left) requires transferring six silicone beads from one set of pegs to another, and then back. Precision cutting task (right) requires cutting an exact circle around a marked piece of gauze.

We recruited 24 subjects without any prior laparoscopic or surgical training ($n = 24$; 17 male, 7 female). They were then randomly assigned into one of the four study groups. Demographic data, including gender, average age, hand dominance, and gaming experience can be seen in Table 3.1. Game experience was self-reported on a scale from 1 to 7, where 1 represented a novice and 7 represented an expert.

For each study group, subject's baseline performance on the two selected FLS tasks were measured. There was then a 30 minute training session, during which they trained on a designated system that depended on their randomized group. These training groups were either: (1) no training (control), (2) standard commercial simulator (3-dMed Trainers, Fig. 3.3 (left)), (3) new training system with a non-inverted mapping, and (4) new training system with an inverted mapping. For the control group, test subjects were asked to wait for 30 minutes. For the group training on a commercial simulator, they were allowed to practice the same FLS tasks that they were tested on. Finally, all the subjects were re-tested on the two selected FLS tests.

Figure 3.3. Systems used for the study included the 3-Med trainer (left), which was used for training the standard simulator group, as well as for conducting the FLS tests, and the new system proposed here (right) with a non-inverted and an inverted instrument mapping.

Table 3.1. Demographic Data ($n = 6$ per group)

	Control group	Standard sim.	Non-inverted	Inverted
Male/Female	3/3	3/3	5/1	6/0
Mean age (years)	22.8	24	22.2	23.3
Right-handed	6	6	6	5
Game experience*	3	3.5	4.3	3

*Game experience was self-reported on a scale from 1 to 7, where 1 represented a novice and 7 represented an expert.

3.3 Evaluation metrics

For typical FLS testing, a final evaluation of pass/no pass will be given to the user upon completion of all the tasks. Although metrics of performance are taken, the specific algorithm is not disclosed by the American College of Surgeons to the public by policy. In addition, there is not a validated visual judgement score used by the surgical community for these simple tasks. We have therefore measured the following objective metrics to use as continuous variables for evaluation.

For the peg transfer task, the total time to complete the task was measured. If the subject could not complete the task (i.e. he or she could not transfer all 6 beads) in the allotted time of 300 seconds, then the maximum time was recorded. The second metric recorded was the number of times a bead was dropped during the specified task. A shorter time along with a smaller number of dropped beads represents a better performance.

For the precision cutting task, the total time to complete the task was measured, and the maximum time allotted was again 300 seconds. In addition, the final cut piece of gauze was examined and compared to the circular path that was printed on the gauze for the subject to follow. Any deviation from the exact print line is noted, and the furthest distance from the cut edge to the print line is recorded.

3.4 Study results

The means and standard deviations for each task and metric are shown in Table 3.2. For task 1, nearly all groups demonstrated improvement between their baseline and final attempts. This improvement is expected as the simplicity of this task makes for a low learning curve, resulting in rapid improvement in simple repetition of the task itself. There was some heterogeneity among baseline performance, as there were more subjects in the control group who used the maximum time allowed for the task compared to the other groups. In general subjects also dropped less beads in their second attempt, but significant improvement was only seen in the control and the standard groups.

Table 3.2. Average values across groups

	Metric	Group	Before	After
Task 1: Peg Transfer Task	Time (sec)	control*	299.8 ± 0.4	189.2 ± 30.4
		standard*	268.2 ± 49.4	181.5 ± 37.1
		non-inv.*	273.3 ± 42.0	240.5 ± 56.1
		inverted	239.2 ± 64.9	217.2 ± 63.8
	Beads dropped	control	4.3 ± 1.6	2.5 ± 1.2
		standard	2.0 ± 1.4	1.2 ± 1.6
		non-inv.	4.3 ± 2.9	2.5 ± 1.4
		inverted	1.8 ± 1.5	2.3 ± 2.3
Task 2: Precision Cutting Task	Time (sec)	control	263 ± 58.4	263.3 ± 57.4
		standard*	280.3 ± 43.5	227.2 ± 50.8
		non-inv.*	257.8 ± 58.9	187.5 ± 43.3
		inverted*	236.5 ± 41.6	178.8 ± 64.9
	Max. deviation (mm)	control	8.7 ± 3.8	7.8 ± 1.6
		standard	6.5 ± 1.9	7.2 ± 2.5
		non-inv.	5.5 ± 1.5	4.3 ± 1.8
		inverted	10.5 ± 5.1	6.5 ± 2.9

*Significant difference between before and after (p<0.05)

For task 2, statistically significant improvements (p<0.05) in completion time are observed in all groups except for the control group, with $p = 0.018$, $p = 0.01$, $p = 0.043$ for the standard, non-inverted, and inverted groups, respectively. The greatest improvement was seen in the non-inverted group, with an average increase of 70.3 seconds, compared to 53.2 seconds and 57.7 seconds, for the standard and inverted groups, respectively. As seen in Table 3.3, compared to the control group, both the simulator group and the non-inverted group showed significantly more improvement ($p = 0.04$ and $p = 0.015$, respectively) (Fig. 3.4). The inverted group also improved more than the control group, with a p-value approaching, but not reaching, significance ($p = 0.058$). In addition to showing improvement compared to the control group, it is important to note that there was no significant difference between the group that trained on the standard simulator and those that trained on either the inverted or non-inverted system (Table 3.3), demonstrating that at least for this initial study, the proposed system performed comparably to the standard one.

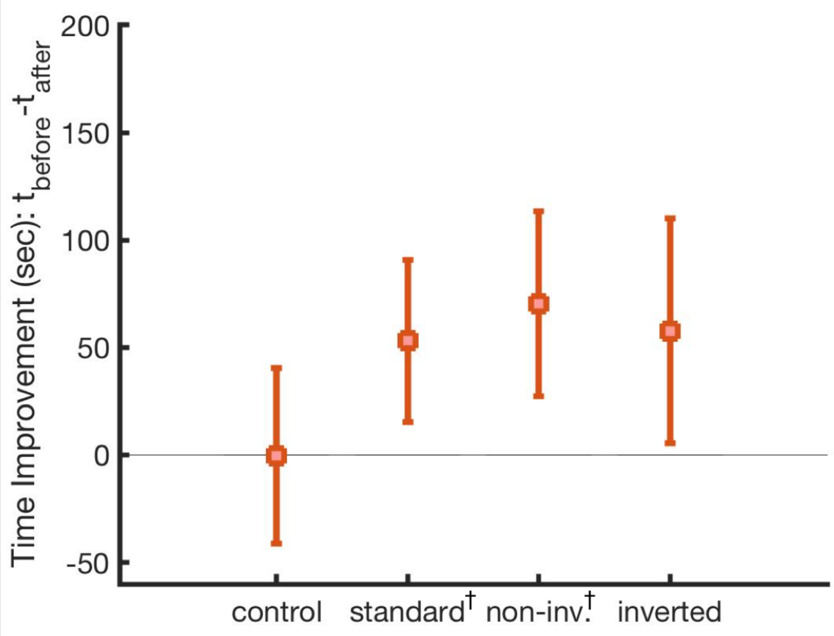

Figure 3.4. Improvement in time to complete the precision cutting task for the four different groups, calculated as the difference between the time for the first and second tests. Significant differences between the training modality and the control group are marked with a dagger (†).

Table 3.3. Comparison between systems
on the time improvement on Task 2

Systems being compared		p-value	significant? ($p<0.05$)
control	standard	0.040	yes
	non-inv.	0.015	yes
	inverted	0.058	approaching
standard	non-inv.	0.480	no
	inverted	0.868	no

3.5 Additional study results

In addition to the preliminary study explained above, a longer study, which lasted four weeks, was also conducted. This second study was designed to evaluate and compare the use of the new training interface, standard laparoscopic training simulator, and video games. There was a total of 15 participants, who were assigned into one of three groups. They were evaluated using the FLS test before and after the month long study. Moreover, the main difference from the preliminary study was that the subjects were allowed to come to practice at any time and for any length of time. Because there was no minimum training time required, the goal was to use this study to understand whether the system could provide a more engaging and motivating training experience.

Due to the difficulties in recruiting a large number of subjects, and the fact that many students were off campus during the study period, we did not have a convincing conclusion on how the new training system can improve basic laparoscopic skills. In the end, the new interface, video games, and standard simulator groups had two, two, and four subjects with no practice time respectively. However, we found a promising outcome after we analyzed the average practice time between each group. Interestingly, the data showed that the video game group had the highest average training time, followed closely by our new training system. The average practice time on the standard simulator was far lower than both of these two groups. This is an exciting result because it means that our new interface could potentially increase user's motivation and engagement. It should be noted that the number of participants was low, and a larger study would need to be performed before drawing any final conclusions.

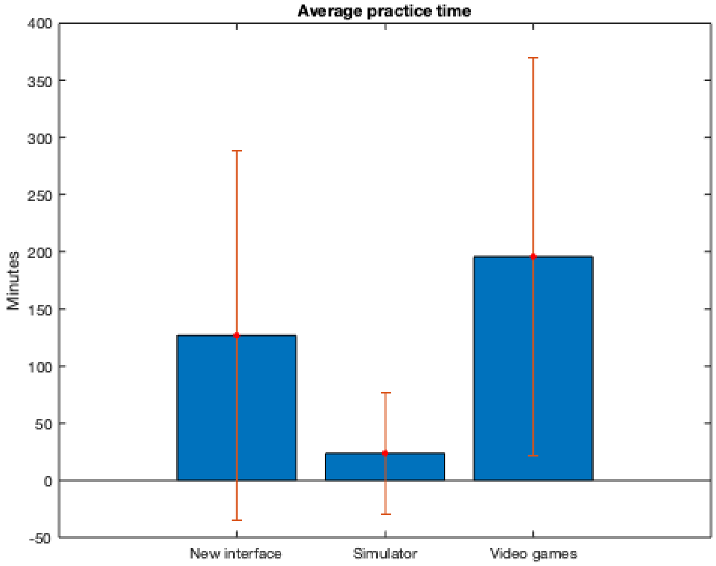

Figure 3.5. A histogram shows the average training time with respect to the new interface group, standard simulator group and video game group.

Chapter 4

Conclusions and Future Work

We developed a low-cost system designed to enable a more engaging and accessible interface for learning basic skills for laparoscopic surgery. The movement and inputs of the customized instruments were mapped to controls for a video game console, enabling users to train by playing a game of their choice. We also performed a preliminary study and demonstrated that even a short (30 minute) training session with the system can lead to significant improvement in laparoscopic skills, such as laparoscopic precision cutting, that is comparable to that seen with standard commercial training systems. The cost of the system in its current form is around \$130 plus an additional \$70 for an Xbox 360 console and controllers, totaling \$200 for the entire system. It should be noted that this cost could be significantly reduced if commercialized and produced at scale, since components could be injection molded and sensors could be purchased at wholesale prices.

The benefits of training on our system are mainly seen when testing on more complex laparoscopic tasks, such as precision cutting, rather than on simpler tasks, such as a peg transfer. This difference in effectiveness is likely due to the fact that the peg transfer task is more rudimentary, and subjects can rapidly improve by simply repeating the task. In contrast, precision cutting requires not only physical proficiency with the instrument, but also continuous fine motion, path planning, and spatial problem solving as the flexible gauze rolls and folds with each detaching cut.

Interestingly, in the precision cutting task, there was no significant difference in the improvement levels between the group that trained on the standard surgical simulator and those that trained on either the inverted or non-inverted system. Considering that the group that trained on the simulator could practice the exact task on the exact system used for testing, therefore gaining muscle memory, these results highlight the transferable benefits between our game-based system and surgical skills.

In addition to what our preliminary study was designed to evaluate, there is an additional unmeasured advantage of our low-cost training system. The standard simulator only comes with a handful of tasks that do not provide any additional incentive for the trainee to practice more. On the other hand, video games are by design intended to capture the interest of their audience and incentivize more playing time. When combined with the practice benefits toward laparoscopic surgery, our proposed system may make a much larger impact on surgeon trainee skill development than the current simulation approach.

In order to thoroughly evaluate whether the system can help with training laparoscopic skills, there are a number of factors that must be investigated in larger-scale studies. First, it is important to look at additional tasks, since this preliminary data suggests that the system may have a larger impact on improving performance for more challenging surgical tasks, but not for simpler ones. Second, it is important to investigate how the duration of training effects learning. We will therefore perform a longer study lasting up to four weeks, where subjects will be asked to train a minimum number of hours per week and their performance on a series of FLS tests will be evaluated before and after. It should be noted that each of these future studies will include a larger number of subjects compared to the preliminary study presented here. In addition, we will evaluate how training with a standard video game controller compares to training with the new system, in order to fully understand any advantages of interfacing with realistic surgical instruments. Finally, we will explore the effects of enabling multi-player training using two of our systems connected to the same video game console in order to investigate whether it helps increase motivation and engagement.

The first version of our new training system could be improved based on suggestions and feedback from our collaborators and the participants. First, the dimensions of the current training box does not allow the user to put it in their bag or carry it very easily. Therefore, we could redesign the training box to be foldable and light weight, enabling the user to carry the device more easily. This would also allow the students to keep one at home where they may not have much space. Additionally, the current system only allows the user to play games on Xbox. There is a need to have a more versatile system which is compatible with any video game platform, including PS4, Android, iOS and PC. Accordingly, the user could play games on any platform and could select any game of his or her choice. Lastly, a different manufacturing and fabrication technique could be used for the next version in order to commercialize our new training system at a even more competitive price.

This thesis, in part, has been accepted by the Journal of Medical Robotics Research, Jui-Te Lin; Shanglei Liu; Arielle Lee; Ryan Broderick; Garth Jacobsen; Tania K. Morimoto. The dissertation author was the primary investigator and author of this paper.

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