Examining the Learning Effects of a Low-Cost Haptic-Based Virtual Reality Simulator on Laparoscopic Cholecystectomy

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Abstract

Virtual reality (VR) surgical training can be a potentially useful method for improving practicing surgical skills. However, the current literature on VR training has not discussed the efficacy of VR systems that are useful outside of the training facility. As such, the goal of this study is to evaluate the benefits of using a low-cost VR simulation system for providing a method to increase the learning of surgical skills. Our pilot case focuses on laparoscopic cholecystectomy, which is one of the most common surgeries currently performed in the United States and is often used as the training case for laparoscopy due to its high frequency and perceived low risk. The specific aim of this study is to examine the efficacy of a low-cost haptic-based VR surgical simulator on improving practicing surgical skills, measured by the change in the learning effect of students.

1. Introduction

In recent years, there has been a verifiable increase in the use of virtual reality (VR) simulation technology for clinical purposes. Although results are varied, studies have shown evidence that the use of VR in surgical training results in improvement in practicing surgical skills [1-3]. Unfortunately, such simulators are expensive and thus are not targeted for use by student populations outside of their training facility. Yet, given the current climate of budget reductions and reduced allocations to aid hospitals to pay for training of new residents and medical students, the development of effective, but low-cost training options, is no longer a luxury, but a necessity. This is especially true given that currently mandated restrictions on the maximum hours in which a resident can participate in clinical activities correspondingly decreases exposure to the number of operations performed by general surgery residents.

As such, for this research, we have designed a low-cost VR surgical simulator for training medical students and have evaluated its usefulness by examining its learning effects in a pilot study with six students. The results from this study are designed to provide preliminary evidence on the efficacy of a low-cost VR surgical training system by comparing the increase in skill learning using the VR training system. This research lays the preliminary groundwork for designing a low-cost virtual reality system for individualizing the learning cycle to improve surgical skills training through adaptation, human observation, and feedback.

2. Background and Significance of Study

2.1. Laparoscopic Cholecystectomy

Laparoscopic cholecystectomy is one of the most common surgeries currently performed in the United States and is often used as the training case for laparoscopy due to its high frequency and perceived low risk. Since its introduction to surgery in the 1980s, the laparoscopic removal of a diseased gallbladder (laparoscopic cholecystectomy) has become the gold-standard [4]. It is the most commonly performed elective abdominal procedure in the United States. However, the performance of this procedure can be technically challenging, and injuries occur in 1 of 200 laparoscopic cholecystectomies performed by experienced surgeons. Common bile duct injuries, which affects the body's ability to drain bile from the liver into the gastrointestinal system, is the leading cost of medical malpractice cases filed against general surgeons. In addition, patients who have sustained common bile duct injuries during the performance of laparoscopic cholecystectomies are susceptible to complex repairs by hepatobiliary specialists and can become extremely ill or die.

The present instructional method for learning laparoscopic surgery involves an apprenticeship to a senior surgeon. Studies have shown that additional training, beyond the hours of initial guidance, is a necessary component for establishing expertise [5]. For example, in the study discussed in [6], surgeons who did not have additional training after completing an 18-

day training seminar were 3.39 times more likely to have at least one complication than those surgeons who had additional training. Moore showed that the chances of a bile duct injury conducted by an experienced surgeon decreased from 1.7% during the first case to 0.17% after 50 cases [7]. Cagir *et. al.* also documented that 90% of bile duct injuries occur within the first thirty cases performed by a practicing surgeon [8].

2.2. Effect of Virtual Reality (VR) on Surgical Skills

Virtual reality simulators enable the creation of interactive 3D environments within which human performance can be motivated, recorded, and measured. Although results are varied, studies have shown evidence that VR training results in technical skills acquisition is at least as good as, if not better than, traditional residency training [1-3]. Especially, a simulation environment composed with a shared learning experience with the specialist's supervision has been found effective [9].

Unfortunately, VR simulators for laparoscopy and colonoscopy training have been reported as still too expensive [11]. Costs of simulation systems were documented as ranging from $5K for most laparoscopic simulators to approximately $200K for highly sophisticated anesthesia simulators. The most promising "low cost" laparoscopic simulator that is currently available in simulated training and evaluation is the McGill Inanimate System for Training and Evaluation of Laparoscopic Skills (MISTELS). The MISTELS system features a trainer box with two 12 millimeter trocars placed on the sides of a laparoscope. Unlike the other studies, this MISTELS system asserts itself on being inexpensive. In comparison with the higher end $200,000 anesthesia simulator, this particular simulator is fairly cheap at a price of approximately $1,680.00 (not including the display monitor). Yet, with budget reductions in current hospital training programs, even this "low cost" simulator may not be practical though for utilization in abundance outside of the training facility.

3. Simulator System Design

The most important goal of any training method is to increase the level of skill that can be brought to bear on a clinical situation. To enable simulation of such procedures as laparoscopic cholecystectomy, the designed virtual training system must employ the same ergonomics applicable to laparoscopic surgery while teaching appropriate muscle memory for the safe performance of a laparoscopic cholecystectomy. As such, our VR surgical simulator (Figure 1) consists of the following three elements: Virtual Reality environment, motion sensors, and haptic feedback.

VR Environment: The virtual environment is designed to depict patient-specific anatomy, as well as surgical instrument interaction, during surgical operations. The primary function of the virtual environment is to provide an emulation of the real surgery application that promotes sufficient learning of surgical skills.

Motion Sensors: In order to employ appropriate muscle memory, the surgical instruments projected within the virtual environment must correlate directly with the user's hand and arm movements. A 3D depth camera is a sensor that can be used to capture and store information associated with a user's body movements. This research used the Microsoft Kinect 3D camera, a low-cost 3D depth camera, to turn our VR environment into a virtual operating room in which student's arm and hand movements control the virtual surgical instruments in the VR environment.

Figure 1. Our mobile VR Surgery Simulator using the Kinect motion sensor and Wiimotes.

Haptic Feedback: In prior work, we have shown that touch-based (i.e. haptic) feedback is an important mechanism for transferring motor skills between expert and novice users [12]. As such, our VR system utilizes haptic feedback as a non-visual means of providing the user information about correct (or incorrect) behavior performed during a surgical operation. For this research, students utilize Wii remote controllers (Wiimotes), which provides a physical emulation of the surgical tools as well as touch-based feedback during the operational steps. Feedback profiles are modified by modulating the strength and duration of the vibrations associated with this low-cost interactive game controller.

4. Simulator Structure

To provide a realistic simulation environment, we construct an expert knowledgebase derived from video footage taken from a surgical endoscope during real cholecystectomy operations (e.g. http:// www.youtube .com/watch?v=7tTGfYCqH5w). Footage was decoded into a sequential set of 15 key stages: 1) Insert trocar/Elevate gall-bladder, 2) Cut adhesion tissue, 3)

Reveal arteries, 4) Expand the split between the arteries, 5) Clip the cystic artery, 6) Clip the vile duct, 7) Cut the cystic artery, 8) Cut the vile duct, 9) Apply heat, 10) Open up peritoneal, 11) Dissect along the edge of the gall-bladder, 12) Continue the dissecting stage, 13) Finish dissecting the gall-bladder, 14) Coagulate bleeding spots, and 15) Take out the gall-bladder through the trocar port.

After key stages were defined, a database that links the corresponding image frames of the video footage to the relevant key stages was used to construct an interactive video tutorial. We then utilized a method called Hidden Markov Models (Section 5.1) to extract the expert surgeon's actions performed during the associated key stage. This information is later used for performance comparison during the student training cycle. Information about each key stage (e.g. image sequences, surgeon's actions, etc.) is encapsulated using a software structure called the automata model (Section 5.2).

The virtual environment itself provides an interactive view composed of the image sequences and the user's virtual surgical instruments (on the left side) and the video tutorial sequence (on the right side) (Figure 2). A training session begins by playing the tutorial video associated with the current key stage of the operation.

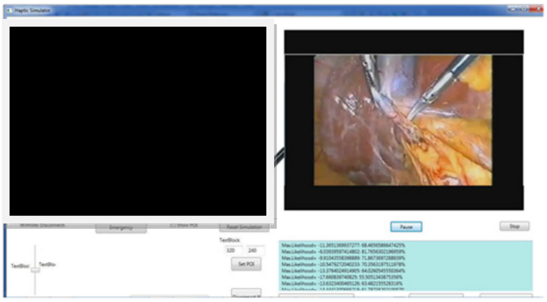
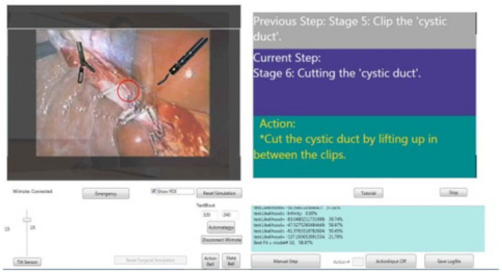


Figure 2. VR Simulator depicting the video tutorial on the right side.

After watching the training video, the user positions himself or herself in front of the Kinect sensor. The system then displays the first image frame of the current stage and starts tracking the user's motion. The user's virtual operations are then compared to the expert's predefined motion to determine success or failure (as explained in Section 5.1). While the user manipulates the virtual surgical instruments, descriptions of the previous and current operational stages as well as the required action are depicted on the right side of the display (Figure 3). For novice users, a region, called the point-of-interest (POI), is revealed to indicate the location where the user needs to place their surgical instrument for achievement of the current surgical operation. The POI is highlighted with a "red" circle as shown in Figure 3.



Previous Step: Stage 5: Clip the 'cystic duct'.

Current Step:
Stage 6: Cutting the 'cystic duct'.

Action:
*Cut the cystic duct by lifting up in between the clips.

Figure 3. Interactive session with a key image frame and virtual-tool movements. The descriptions on the previous and current operational stages as well as the required action are displayed on the right side.

When the user first positions their instrument in the POI and initiates movements associated with a surgical action (such as cut, clip, etc.), the system provides a haptic vibration on the Wiimote and begins tracking the user's motion. If the user takes the "right" action in a given time limit, the system will give the user a positive haptic feedback, and the interactive view transitions to the next key stage of the operation. If the user does not implement the correct action for the stage in a given time limit, the system will replay the tutorial video associated with the corresponding surgical step (Figure 4), based on the assumption that the user requires retraining on the current operational steps.

Figure 4. Video tutorial mode for the corresponding stage in case of a "time-out".

5. Algorithms for Simulator Operation

For real-time interaction with the user, the VR surgical simulator needs to constantly determine two categories of information. First, the system is required to track the human's hand-motions (both left and right hands) and determine if their motion is the correct motion related to the current stage (i.e. surgical step).

Secondly, the system needs to keep track of the progress of the user in the scope of the full operational sequences and provide the correct set of sequences (e.g. transition to the next stage or change to tutorial-video mode). This section presents the details of the underlying algorithms applied for classification of the user's motion and the operations for transitioning through the simulation system.

5.1. Hidden-Markov Model (HMM)

The Hidden-Markov-Model (HMM) is a well-established statistical model that can analyze a sequence of data and interpret the internal "hidden" relations between the elements in the sequence [13,14]. The HMM assumes a Markov model composed of interconnected ″hidden" states, observations, and state transition probabilities. If a HMM model is predetermined, the HMM model can determine the maximal likelihood between an original sequence of training data and a new sequence of data, and tell if the new data fits the model.

Although a surgical operation may consist of many different steps—such as preparing surgical tools, inserting trocars, and injecting medicine—each surgeon performs these surgical steps in their own stylistic manner. However, these operations do have generalizable speed and trajectory characteristics commonly defined for successful achievement of the surgical step. Either through practice or through verbal correction from an expert surgeon, a student begins to learn these characteristics in a typical training scenario. Thus, for the purposes of our simulator, we wish to evaluate the student's surgical instrument usage in a physical action domain and compare these actions with the expert surgeon's. HMMs are utilized to enable this performance comparison between student and expert.

Specifically, we represent the motions of a user's two hands, which correlate with the virtual movements of the surgical tools in a simulator, using discrete valued sequences. When a user performs a surgical operation, we need to focus not only on the trajectory of the motion, but also the speed variances of the motion to accurately compare it with the expert's motion. To efficiently perform discretization while capturing both characteristics, we observe the speed variations of the user's hand motion with regard to directions on the two-dimensional domain as visualized in Figure 5 and transform it into a sequence of nine integer values: {0,1,2,3,4,5,6,7,8}. Figure 5 illustrates an example sequence captured from the cystic artery cutting motion. The discretized information is processed by HMM models for the expert's motion data, and a match between student and expert can be found if the student's model with the highest probability output correlates with the expert's action sequence for the current surgical step. Through this process, the system can determine whether the user has implemented a given surgical step correctly or not (as compared with the expert).

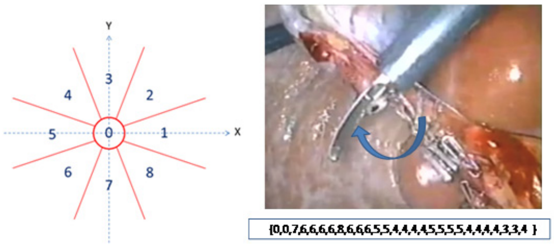


Figure 5. Discretization of hand-motion in the speed domain, and a sample representation of a cutting movement. The '0' region represents the user's hand is stationary and the '1' region means the user is moving the hand toward right side on the image, etc.

5.2. Automata Model

While the HMM model governs the microscopic operation of the tracking and comparison of human motion during interaction with the system, the automata model is in charge of the macroscopic operation of the system. The automata is a well-established theoretical model that describes higher-level states and transitions associated with a sequence of dynamic operations [15]. The automata consists of nodes (automatons) and branches (transition links). In our simulation system, we have defined 15 key stages and thus we define an automata model with 15 automatons. In essence, each automaton is in charge of 1) displaying the key image frames and points of interest to the user, 2) tracking and recognizing the user's hand motions, 3) comparing the user's motion with the right action (expert surgeon's movement), and 4) implementing follow-up actions according to achievement of the goal (e.g. transition back one sequence if failure, play corresponding video frames in case of time-out, and progressing to the next stage when the correct action is accomplished). The interesting aspect of the automaton in our system is that each automaton is in charge of training the user based on the specific details associated with the current stage of the operation. For example, if the user takes the right actions on the POIs in a given time limit, it will mark the stage complete and transition to the next stage determined in the automata. However, if the user does not satisfy the time limitation or perform the right actions, it will stop the simulation and play the tutorial video corresponding to the operational stage. By using this construct, specific learning parameters can also be extracted to understand which stages cause the most difficulties for students (which will be helpful for future training).

6. Experimental Design

We have designed an experimental study with human subjects to evaluate the performance and effectiveness of our system in the learning of the cholecystectomy operation. The protocol for the experiment is as follows:

1. Subjects are briefly introduced to the concept of cholecystectomy operations and the purpose of this experiment.
2. Subjects watch the first half of the cholecystectomy video tutorial (one minute).
3. Subjects are briefly introduced to the VR surgical simulator (sensor, haptic and sound feedback, and the message guidelines on the GUI) and shown how to control the virtual surgical instruments
4. Subjects use the VR surgical simulator to train on the key stages 1-6 of the cholecystectomy operation
5. Subjects are allowed to stop the training at any time and the log data is saved.

The experiments are designed to be repeated three times with at least an hour interval between experiments per subject. The measurements and evaluation criteria are as follows: overall simulation time, average number of tutorial video plays, and average number of surgical steps.

7. Results

A total of one expert surgeon from Grady Memorial Hospital and six student subjects fully participated in the experiments. Data collected included - time required to transition through each of the key stages 1 through 6 of the cholecystectomy operation; the number of times the tutorial activated for each stage; and the number of surgical operations implemented during each key stage.

Overall simulation time was calculated for each subject based on the total time required for a student to complete stages 1 through 6. Simulation time was used to determine how well the user adapts to the system, i.e. how easy the system is to learn to use. The results in Figure 7 show that users took, on average, 4 minutes and 30 seconds to complete the virtual surgical operation at the first instance of training (with a standard deviation of 130 seconds), but after two more trials the average time decreased to 1 minute and 15 seconds (with standard deviation of 13 seconds). This presents preliminary evidence that the users can easily learn to use the system and increase their skill performance.

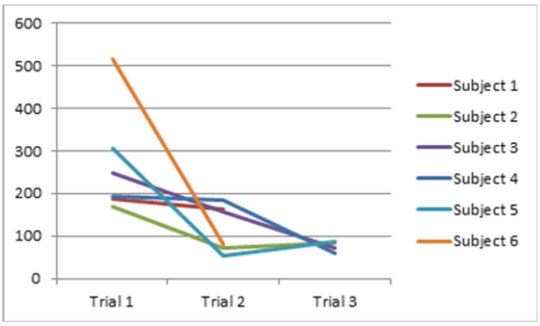


Figure 7. Simulation time of subjects per trial (unit=seconds).

The average number of tutorial video plays activated during the subject's trial was calculated to estimate how well the subject understands the operational steps of the surgery (Figure 8). Initially, the subjects, on average, exhibited incomplete knowledge on the surgical steps, which resulted in approximately 6.5 tutorial plays being activated on average (with standard deviation of 5.54 times). However, after two more trials, the subjects almost mastered the knowledge on the surgical steps and finished the states with only 0.5 times of tutorial video being activated (with standard deviation of 0.58 times).

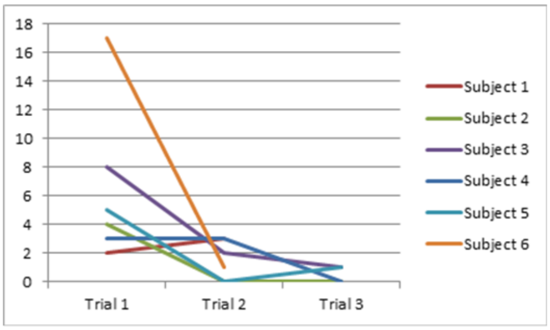


Figure 8. Number of tutorial video modes activated per subjects.

The average number of actions per each key stage was calculated to analyze how accurate the subject has learned the skills needed to complete the cholecystectomy operation (Figure 9). A total of 12 surgical steps/actions (which equates to an average of 2 actions per key stage) were required to complete stages 1 through 6. On average, the subjects executed about 7.24 actions for each stage at the initial trial. However, after two more trials, the subjects could complete each stage in only 2.3 actions (with standard deviation of 0.55).

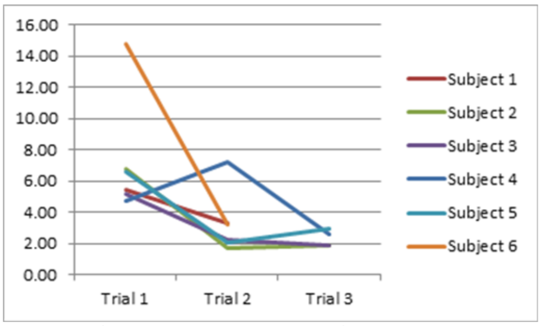


Figure 9. Average number of actions per key stage.

8. Conclusion

This research provided preliminary evidence on the efficacy of a low-cost VR system on improving surgical laparoscopic cholecystectomy skills by examining its learning effect on students. The key focus of this research was to evaluate a low-cost VR system that could function as an in-home training system for students. Given that most students possess a computing platform, the resulting cost of the system totals $250 in peripherals (Kinect and Wiimote). By examining the learning effect on novice users, we have preliminary data that shows the VR surgical simulator not only reduces errors in the individual actions required to perform the procedure but decreases the overall time necessary for completing the sequence of operations. These are key features required for providing evidence on the efficacy of a low-cost VR system. Future efforts include expanding the number of stages used in evaluating the training outcomes, exploring the inclusion of training on other skill-sets, and providing a post-experiment questionnaire to evaluate user perception, as compared to the qualitative results on performance, and evaluating transfer of VR-learned skills to the operating room.

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