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Mastering Instruments Before Operating on a Patient: The Role of Simulation Training in Tool Use Skills

Bin Zheng, MD, PhD¹, Bo Fu, BSc¹, Thamer A. Al-Tayeb MD², Yi Fan Hao², and A. Karim Qayumi MD, PhD²

Abstract

Background. We examined the impact of tool complexity on surgeons’ performance and evaluated the value of using a simulation-based program for reducing training cost. Methods. Three pairs of surgical graspers with increasing mechanical complexity, which were designed for open, laparoscopic, and endoscopic procedures, were used in performing a simple object transportation task. Task times and mental workload of 17 surgeons were compared using all 3 variations of the graspers to test the impact of tool complexity on surgical performance. Subsequently, 4 of these surgeons decided to enter a 3-week training phase and practiced with these 3 surgical instruments on a daily basis. Learning curves were plotted to examine the value of using simulation for proficiency training with these tools. Results. Task time was significantly prolonged as tool complexity increased. Practice in a simulated environment shortened the task time significantly and moderately reduced mental workloads. However, the difference in task time varied among the 3 types of tools. Between days 1 and 9, task times for each type of grasper were reduced by 55% (endoscopic), 42% (open), and 22% (laparoscopic). Conclusions. Tool complexity may degrade a surgeon’s performance. Extensive simulation training programs are important for surgeons to gain proficiency in handling a tool before they practice on patients.

Keywords
simulation, tool complexity, learning curve, laparoscopy, NOTES, surgical education

Introduction

As minimally invasive surgery becomes standard, large numbers of surgical procedures have been performed using laparoscopic and endoscopic instruments. While patients prefer such an approach with less trauma associated with a procedure,¹ surgeons repeatedly report an increasing level of mental and physical challenge when they perform laparoscopic procedures. Skills developed from open procedures are often insufficient for manipulating intricate laparoscopic instruments.²⁻⁵ There is a need for surgeons to acquire skills in using laparoscopic and endoscopic instruments.

Developing a new set of skills with a tool is not a trivial challenge for a human operator.² Physical properties, such as weight and surface texture of the tool, and mechanical properties, such as the number of hinges and the size difference between tips and handles, regulate our interaction with the tool and alter the force application from the hands.³ In addition, the changing task requirement will also affect the way we interact with a tool.³ This can be demonstrated by having the operator hold an identical tool for different tasks. For example, most surgeons grip a pair of hemostats with their fingers when asked to clip a bleeding vessel, but will hold the hemostats in their palms when placing a drainage tube through the chest wall of a patient. Our previous study on the human tool interaction has revealed that the mechanical complexity of a tool can modify the movement coordination built among motor segments of a human operator’s upper limb.⁹

Compared with instruments for open procedures, instruments designed for performing laparoscopic, single-port access, and endoscopic procedures are more complicated with an increasing number of hinges and
degrees of freedom. The first goal of this project was to carefully assess the influence of the tool complexity on surgeons' performance.

In cases where complex surgical instruments are inevitable for performing a procedure, such as using flexible instruments for an endoscopic procedure, surgeons will need sufficient time to train with the instrument before they are ready to operate on patients. Surgeons need to coordinate their motor systems over 2 different interfaces when learning the skill set for using a tool: the surgeon–tool and tool–patient interfaces. The surgeon–tool interface describes how the surgeon interacts with the tool held in his hands, whereas the tool–patient interface describes how the tool manipulates the surgical site inside the body of the patient. If a surgeon has difficulty in controlling the tool in his or her hand, he or she cannot safely perform the procedure as the tool–hand coordination has not been built up, and his or her attention will be frequently drawn back to the tool from the patient. We believe that surgeons should acquire skills in using the tool before entering the operating room. We also argue that skill training in surgical tools usage can generally be fulfilled with simulation in a laboratory environment to promote patient safety. The second goal of this project was to examine the learning process of surgeons in controlling complex surgical instruments and test the value of using simulation for training skills in tool usage for laparoscopic and endoscopic procedures.

We asked surgeons to complete a single ring transportation task by using 3 different types of surgical graspers, each designed for either open, laparoscopic, or endoscopic procedures 3 times per week for 3 weeks. The learning process was monitored by task time and self-reported workload. We have 2 working hypotheses: First, the surgical tools with greater complexity will degrade surgeons' performance when the task is kept identical; second, simulation training will provide sufficient training for surgeons to achieve the required level of skill for mastering tools with different mechanical properties.

**Methods**

**Participants**

Seventeen surgeons from the General Surgery Department of University of British Columbia responded to an e-mail call for subjects and were recruited to participate in this study. Ethical approval was granted by ____ Participants included 2 attending surgeons, 3 laparoscopic fellows, and 12 surgical residents. The majority of participants were right-handed (14/17), and all had normal or corrected-to-normal vision.

**Apparatus**

The study was carried out in the Surgical Skills Laboratory, based at the Centre of Excellence for Surgical Education and Innovation of the Department of Surgery at the University of British Columbia. A commercially available training box (Laparoscopic Trainer; 3-D Technical Services, Franklin, OH) was used to create a standardized work environment for both laparoscopic and endoscopic procedures. A digital video camera was mounted inside the training box for visual presentation of the work field. The image was displayed to a 10-inch LCD color monitor placed on top of the training box.

Two 10-mm ports on the front wall of the training box were used for insertion of laparoscopic instruments (2 pairs of 5-mm laparoscopic Maryland graspers; Ethicon Endo-Surgery, Cincinnati, OH). A third 10-mm port was custom designed for this project and was located between the 2 intrinsic ports. Through this middle port, we placed a dual-channel therapeutic endoscope (GIF-2T160; Olympus, Tokyo, Japan), which carried 2 pairs of endoscopic forceps through its working channels (Jumbo Biopsy Forceps with Serrated Jaw; Boston Scientific Corp, Natick, MA).

The training box was placed on top of a 30-inch high table. The table also served as a platform for performing the open surgical procedure that was conducted using 2 pairs of hemostats (Almecon Instruments, Tuttingen, Germany). The tool complexity from simple to complex is arranged from the open to laparoscopic to endoscopic instruments.

The hemostats used in the open procedure include one hinge by which surgeons can control the tips' movement in a straightforward manner. Each pair of laparoscopic and endoscopic graspers has multiple built-in hinges that increase the control difficulty. It is difficult for surgeons to predict the movements between the hands and tips of the instruments, especially when using the flexible endoscopic forceps. The endoscopic forceps themselves do not have the ability to converge their tips. In performing coordination tasks, the surgeon must twist the tip of the endoscope to translate the intended movements to the tips of the forceps. The position and force controls for manipulating the endoscopic instruments are much more complex compared with manipulating a pair of laparoscopic instruments.

Surgeons were required to perform a standardized task with all 3 types of instruments. A data-recording sheet was developed by counterbalancing the order of participants in using the open, laparoscopic, and endoscopic instruments.

**Tasks and Procedure**

Prior to data collection, participants first read an information sheet detailing the specific aims of the study and
Zheng et al provided written informed consent for participation. Prior to beginning the tasks, each surgeon’s demographics, including level of training and surgical and laparoscopic experience, were obtained through a pretest questionnaire. The study was divided into the performance assessment phase and the simulation training phase. In the assessment phase, the participants were given a practice trial to ensure a correct understanding of the task. Surgeons were required to transport a 3-mm plastic ring between 2 predetermined locations on a standard training tool called the Sea Spikes Pod (Chamberlain Group, Great Barrington, MA). The Sea Spikes Pod consists of flexible rubber spikes of different lengths, shapes, and colors (Figure 1). For the open surgery tasks, the Sea Spikes Pod was placed on the table; in the laparoscopic and endoscopic tasks, the Sea Spikes Pod was fixed to the bottom of the training box.

The task started by reaching and picking up the ring resting on the yellow spike in the left field of the pod, transferring the ring between the tools, and then placing it on to the red spike to the right field of the pod (Figure 1). The task was then repeated in the reverse sequence, by bringing the ring back to the yellow spike. The grasper that was not in use for transport was required to touch the resting area at the central bottom of the pod (Figure 1). This task was repeated using all 3 types of surgical instruments with a counterbalanced order among different participants.

At the end of the performance assessment phase, participants were given an opportunity to enter the simulation training phase. They were required to allocate 3 practice days per week and completed the entire training phase over a period of 3 weeks. On each practice day, they were required to practice 20 minutes on each of 3 types of surgical instrument, followed by performing a test trial to assess their performance on that day. One week after the last practice day, the participants were called back to the lab to assess their short-term skill retention. Four weeks after the last practice day, participants were called back to the lab to assess their long-term skill retention. Because of time constraints, only 4 surgeons participated in this phase of the study and completed all training trials. This group consisted of 2 clinical fellows and 2 senior residents. All 3 of these surgeons had obtained a sufficient amount of experience in performing laparoscopic procedures using conventional instruments but had no experience in using the endoscopic instruments.

**Performance Assessment and Statistics**

Performance was measured by task time in seconds. The task time was recorded starting when the grasper first touched the ring and ending at the moment when the grasper touched the bottom of the pad after the ring was brought back to the original spike.

Immediately at the end of each subject’s trial, the subjective assessment of mental workload was conducted using the PC-based NASA Task Load Index (NASA-TLX) score. NASA-TLX requires participants to rate their experienced levels of mental, physical, and time demands associated with workload on a scale of 20 points, as well as their effort, performance, and frustration during a performance. NASA-TLX has been used extensively in a variety of projects for assessing mental workloads of surgeons.

To test hypothesis 1, the task performance and NASA-TLX of 17 subjects on using 3 different types of surgical tools were compared using a within-subject analysis of variance (ANOVA) with repeated-measures analysis. The learning curves of the 4 surgeons over the 3-week training period were plotted to test hypothesis 2. Task performance over 8 weeks, including 9 practice days in the first 3 weeks, the short-term follow-up in the fourth week, and the long-term follow-up in the eighth week, were assessed by a 11 (day) × 3 (tool) ANOVA. Skill retentions were examined for 3 types of surgical procedures between last week in training (data average over days 7, 8, and 9) and the 2 follow-up days in week 4 and week 8 by a separate ANOVA. P value of < .05 was considered significant. Results are reported as mean ± standard deviation unless otherwise stated.

**Results**

A total of 17 surgeons participated in the assessment phase of this study and completed the task by using 3 different types of surgical tools. Average task time while
using endoscopic instruments was 229 ± 110 seconds. This was 7.4 times and 12.9 times longer, when compared with task times completed using the laparoscopic (31 ± 11 seconds) and open (18 ± 8 seconds) instruments \( (P < .001) \). Surgeons’ mental workload increased when using the endoscopic instruments (NASA TLX = 49 ± 16), compared with using laparoscopic (NASA TLX = 42 ± 12) and open instruments (NASA TLX = 35 ± 11; \( P = .010 \); Table 1). Post hoc analysis using the Bonferroni correction for pairwise comparisons revealed significant differences in task time between using open and endoscopic instruments \( (P < .001) \), and laparoscopic and endoscopic instruments \( (P < .001) \). The NASA-TLX was increased significantly, from using open instruments to using endoscopic instruments \( (P = .003) \), but not between laparoscopic and open \( (P = .116) \), or laparoscopic and endoscopic instruments \( (P = .122) \).

The learning curve of the 4 surgeons over the 3-week training phase is plotted in Figure 2. Practice significantly shortened the surgeons’ task times when using the open \( (P = .043) \), laparoscopic \( (P = .014) \), and endoscopic instruments \( (P < .001; \text{Table } 2) \). Practice reduced surgeons’ mental workloads for using all 3 types of instruments but not significantly (Figure 3). Surgeons’ task times over the 3-week training period were reduced by 42%, 22%, and 55% for open, laparoscopic, and endoscopic instruments, respectively.

Examination of skill retentions found that task time remained steady in both open (week 3, 11 seconds; week 8, 10 seconds; week 9, 12 seconds; \( P = .590 \)) and laparoscopic procedures (week 3, 25 seconds; week 8, 28 seconds; week 9, 26 seconds; \( P = .591 \)), and decreased slightly in endoscopic (week 3, 199 seconds; week 8, 192 seconds; week 9, 185 seconds; \( P = .958 \)); but no significant differences were found. NASA-TLX scores also showed insignificant changes between the last training week and the 2 follow-up weeks for all 3 types of procedures (open: \( P = .815 \); laparoscopic: \( P = .772 \); and endoscopic: \( P = .976 \)).

**Table 1.** Impact of Tool Complexity on Surgeons’ Task Performance and Mental Workload.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Task Time (Seconds)</th>
<th>Post Hoc (P Value)</th>
<th>NASA-TLX</th>
<th>Post Hoc (P Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open</td>
<td>18 ± 8</td>
<td>.554</td>
<td>35 ± 11</td>
<td>.116</td>
</tr>
<tr>
<td>Laparoscopy</td>
<td>31 ± 10</td>
<td>&lt;.001</td>
<td>42 ± 12</td>
<td>.122</td>
</tr>
<tr>
<td>Endoscopy</td>
<td>229 ± 110</td>
<td>&lt;.001</td>
<td>49 ± 16</td>
<td>.003</td>
</tr>
</tbody>
</table>

Abbreviation: NASA-TLX, NASA Task Load Index.

**Figure 2.** Task times decreased of surgeons over the practice in 3 weeks.

Discussion

Our first hypothesis was supported. Compared with open procedures using simple tools, surgeons’ performance while using flexible instruments during endoscopic procedures degraded significantly (12.7 times longer in task time). Results were obtained in a controlled laboratory environment with an identical surgical task, therefore the
increased levels of complexity presented by endoscopic tools, which consist of multiple articulations and degrees of freedom, was the main factor in hampering task performance. Laparoscopic instruments also have complex mechanical properties, but surgeons’ performance was less deteriorated on laparoscopic procedures when compared with endoscopic procedures. This may be because of the fact that surgeons who participated in this study already acquired skills in manipulating laparoscopic instruments during their surgical training; they did not, however, have a comparable level of training with endoscopy. For safe performance, surgeons should be given a sufficient training phase with the tool (flexible instrument) before operating on patients with a therapeutic endoscope.

However, many current surgical training courses do not integrate tool training into their curriculum. The weekend courses designed for laparoscopic, single-port access, and endoscopic surgeries normally begin with a didactic lesson that is followed by a hands-on session on how to perform the procedure, often in a cadaver or animated lab. It is wasteful to use these expensive training models if a surgeon is still struggling with manipulating the tools with his or her hands.

The second piece of evidence in this study demonstrated that simulation-based training can assist surgeons in overcoming their difficulties with more complex instruments using simple bench-top models, which supports our second research hypothesis. The underlying mechanism of surgeons in adapting a tool into their native movement system is still not fully understood. However, it is known that surgeons need to go through several learning phases, including recalibrating the motor plan by integrating the mechanical properties of the tool into the motor system, and generating movements with adjustments to the hands to ensure the outcome from the endpoints of tools to fulfill a task goal.6,9

The tool adaption process of a human operator with a tool requires practice time. Once the adaptation process with a tool is completed, movement control with a tool becomes automatic.5 At this stage, tools became a natural extension of the limbs, and surgeons will have the opportunity to reduce the burden of mental workload related to tool

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### Table 2. Training in Simulation Helped to Shortened Task Times and Alleviated Workloads of Surgeons.

<table>
<thead>
<tr>
<th></th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>Day 2</td>
<td>Day 3</td>
<td>Day 4</td>
<td>Day 5</td>
</tr>
<tr>
<td>Task time (seconds)</td>
<td>Open</td>
<td>Laparoscopy</td>
<td>Endoscopy</td>
<td>Open</td>
<td>Laparoscopy</td>
</tr>
<tr>
<td>Open</td>
<td>17 ± 4</td>
<td>17 ± 3</td>
<td>17 ± 9</td>
<td>13 ± 3</td>
<td>11 ± 2</td>
</tr>
<tr>
<td>Laparoscopy</td>
<td>39 ± 12</td>
<td>36 ± 8</td>
<td>30 ± 5</td>
<td>33 ± 4</td>
<td>28 ± 6</td>
</tr>
<tr>
<td>Endoscopy</td>
<td>369 ± 66</td>
<td>257 ± 86</td>
<td>209 ± 17</td>
<td>205 ± 64</td>
<td>214 ± 72</td>
</tr>
<tr>
<td>NASA Task Load Index</td>
<td>Open</td>
<td>Laparoscopy</td>
<td>Endoscopy</td>
<td>Open</td>
<td>Laparoscopy</td>
</tr>
<tr>
<td>Open</td>
<td>26 ± 20</td>
<td>26 ± 8</td>
<td>31 ± 24</td>
<td>30 ± 23</td>
<td>30 ± 20</td>
</tr>
<tr>
<td>Laparoscopy</td>
<td>49 ± 25</td>
<td>50 ± 27</td>
<td>54 ± 16</td>
<td>45 ± 25</td>
<td>48 ± 28</td>
</tr>
<tr>
<td>Endoscopy</td>
<td>88 ± 28</td>
<td>82 ± 22</td>
<td>71 ± 35</td>
<td>84 ± 18</td>
<td>61 ± 37</td>
</tr>
</tbody>
</table>

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### Figure 3. Mental workloads decreased of surgeons over the practice in 3 weeks.
manipulation. The surgeon can transfer the spared mental resources to decision making for solving problems arising during the operation. Unfortunately, participants did not report a significant drop of workloads when assessed by NASA TLX. Nevertheless, during the 3-week training phase, the surgeons achieved 55% time reduction and 44% alleviation in mental workload after practicing with the flexible endoscopic tools in simulation. This evidence was encouraging and should advocate the integration of simulation into surgical training courses with a reasonable cost.

The main limitation of this study was that the task in the simulation model was oversimplified. It could not represent the real surgical tasks that are performed within actual surgery. In future studies, we will select and design more appropriate tasks with a higher level of fidelity to better match learning goals. Nevertheless, the study’s findings could lead to greater awareness from surgical educators and encourage surgeons to introduce simulation to their surgical curricula.

Declaration of Conflicting Interests
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