The Effect of Haptic Feedback on Laparoscopic Suturing and Knot-tying: A Learning Curve Study

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Haptic feedback has been shown to benefit performance in various laparoscopic surgery tasks. However, providing haptic feedback to novice trainees in the early stages of training may be distracting. A controlled experiment was conducted to investigate the effect of haptic feedback on the learning curve of a complex laparoscopic suturing and knot-tying task. It was hypothesized that subjects would perform better and reach the first plateau in the learning curve earlier with haptics than without. Twenty novices participated in eighteen one-hour training sessions. Results indicated that training with haptics was not significantly different from training without haptics after five hours of practice. However, those who learned with haptic feedback were more consistent in their task performance and had a shorter learning curve. Therefore, haptic feedback may be omitted in a laparoscopic surgical simulator in early training provided that extensive training is possible.

INTRODUCTION

Surgical training has traditionally followed the apprenticeship model of “see one, do one, teach one”, until recently. Since the introduction of laparoscopic surgery, surgeons need another approach to training to ensure technical competency before entering the operating room. This is critical because additional sets of skills are required in laparoscopic surgery compared to open surgery, such as operating with limited visual area of anatomy and lost depth perception due to a 2D view on the video screen, overcoming the fulcrum effect of the tool, and manipulating the tissue and organ appropriately to compensate for distorted haptic feedback introduced by long tools, abdominal wall, and trocars (Picod, Jambon, Vinatier, & Dubois, 2005; Perreault & Cao, 2006).

Recently, a transformation in the approach to surgical training has taken place, with technological innovation such as surgical simulators and virtual reality simulation playing an increasingly important role (Seymour, Gallagher, Roman, O’Brien, Bansal, Anderson, et al, 2002; Sutherland, Middleton, Anthony, Hamdorf, Cregan, Scott, et al, 2006). Simulators have emerged as the preferred choice for training environments for both practical and ethical reasons. However, the fidelity of simulation remains a challenge for the engineering community and an empirical question for surgical educators. Although low-fidelity simulators have proven to result in statistically significant skill transfer to the operating room (Grantcharov, Kristinasen, Bendix, Bardram, Rosenberg, & Funch-Jensen, 2004; Seymour, et al, 2002), it is generally considered that realistic simulations with multisensory feedback could provide better learning experience and better outcomes (Lathan, Tracey, Sebrechts, Clawson, & Higgins, 2002). However, Champion and Higgins noted in their review of aviation training literature (Champion & Higgins, 2000) that irrelevant stimuli in a high-fidelity simulator actually made task learning more difficult as the novice trainee had to learn to ignore these stimuli. Some researchers have suggested that the level of simulator fidelity be matched to the stage of skill acquisition (e.g., Champion & Higgins, 2000; Gandzas, Adrales, & Park, 2004).

The role of haptic feedback is of special interest in surgery, and in particular, laparoscopic surgery, because it is critical in the discrimination of healthy versus abnormal tissues, identification of organs, and motor control. Force feedback has been shown to improve robot-assisted knot-tying with fine suture (Kitagawa, Okamura, Bethea, Gott, & Baumgartner, 2002), reduce the overall forces applied and the number of accidental incursions into sensitive structures, but not the rate and precision of dissection (Wagner, Stylopoulos, & Howe, 2002). It also improves performance in determining tissue properties, but not in tissue holding tasks (Heijnsdijk, Pasdeloup, Van der Pijl, Dankelman, & Gouma, 2004). Force feedback affects force application, task completion time, and the straightness of suturing (Moody, Baber, & Arvanitis, 2002).

Recently, several studies were conducted to investigate the impact of haptic feedback in surgical training, especially during the early stages of training. Our own research has shown that haptic feedback not only enhances performance of simple laparoscopic surgery training tasks, but also counters the effect of cognitive distraction (Cao, Zhou, Jones, & Schweitzberg, 2007). Another research indicated that early exposure to haptic feedback enhances performance in surgical simulator training of diathermy task, and thus haptic feedback could be important in the early training stage of skill acquisition (Strom, Hedman, Sarna, Kjellin, Wredmark, & Fellander-Tsai, 2006). Based on surgeons’ opinions, haptic feedback is considered a necessity and training on box trainer is preferable over virtual reality simulator systems for laparoscopic suturing because VR simulators lack realism and haptic feedback (Botden, Torab, Buzink, & Jakimowicz, 2007).
Previous studies on learning curves using laparoscopic surgery trainers or simulators showed different results on various tasks. Research has shown that the learning curve based on the speed of task completion reached a plateau after only three trials while performance accuracy did not stabilize after ten trials on a box trainer (Smith, 2001). A study investigating the effectiveness of structured training methods for learning to perform an intracorporeal knot-tying task using a box trainer showed significant improvement after one trial, with further significant improvement at the end of ten trials (O’Connor, Schwartzberg, & Cao, 2007; Rosser, Rosser, & Savalgi, 1997). Two other studies on the learning curve where trainees used the virtual reality trainer, MIST-VR, showed that performance was significantly improved after a 5-day training period (Kothari, Kaplan, DeMaria, Broderick, & Merrell, 2002) and that performance variables reached a plateau by trial 5 (Gallagher, & Satava, 2002). Others suggested that the learning curves of a knot-tying task did not show significant differences between the MIST-VR and box trainer on performance time for any trial (Pearson, Gallagher, Rosser, & Satava, 2002).

Research on the effect of haptic feedback for initial and more extensive training of laparoscopic surgery, especially for a complex task such as laparoscopic suturing and knot-tying, is lacking. Our study was conducted to investigate the effect of haptic feedback on the learning curve in laparoscopic surgery with extended training. We hypothesized that with haptic feedback, trainees would reach the first plateau in the learning curve earlier than those trained without haptic feedback. Also, subjects trained with haptic feedback would perform better throughout the learning phase than those trained without haptic feedback.

MATERIALS AND METHODS

Subjects

Twenty graduate and undergraduate students (6 females and 14 males) without any prior laparoscopic surgery experience participated in this experiment. Nineteen of the subjects were right-handed, and one was ambidextrous. Subjects were between 21 and 34 years old.

Apparatus and Procedures

Two surgical training simulators, MIST-VR and ProMIS (see Figure 1) were used in this study. The MIST-VR is a virtual reality simulator that does not provide haptic feedback. It is comprised of a computer, a monitor, and a laparoscopic tool base. The ProMIS is a physical simulator that provides haptic feedback similar to that experienced in actual surgery. It is comprised of a life-size model of the upper torso with a light source, a computer, a monitor, and laparoscopic tools.

Identical suturing tasks were performed on each of the simulators. Subjects used two needle drivers to suture and form two single loop half-square knots to complete one square knot. In MIST-VR, the task was performed on a virtual organ, while in ProMIS, the task was performed on a Penrose drain attached to a Velcro block.

Prior to starting the study, all subjects received one hour of instruction given by an expert surgeon. The instruction consisted of an introduction to laparoscopic surgery and demonstrations of open surgery suturing and laparoscopic surgery suturing. After this, subjects practiced the task one hour a day, six days a week, for three consecutive weeks for a total of 18 training sessions. During the hour-long training sessions, subjects attempted as many knots as possible. Further instruction was given to the subjects if they appeared to be struggling with the task. Moreover, knowledge of performance results were shown to the subjects at the end of each trial. These results were time to task completion, instrument path, and instrument smoothness on ProMIS; time to ask task completion, errors, and overall score on MIST-VR.

Figure 1. MIST-VR (left) and ProMIS (right)

Experimental Design and Data Analysis

The experiment included two conditions: Haptics and No-Haptics. Subjects were randomly assigned to one of the two conditions. There were ten subjects for each condition. Those in the Haptics condition performed the task using the ProMIS simulator, while those in the No-Haptics condition used the MIST-VR simulator. The performance measure was the time to complete one square knot successfully. Unsuccessful knots were not counted.

Individual learning curves were obtained for the time measure for each subject. Analysis of variance within each group between the first session and all subsequent sessions, and between the last session and all prior sessions were conducted using one-factor ANOVA with a Scheffe test. Paired t-test was performed to compare the time to task completion, variance of task completion time per session, and the best performance time of the session for the two groups. The time to task completion and between subject variance in the training were also analyzed using paired t-test.
Table 1. Analysis of variance between learning curves.

<table>
<thead>
<tr>
<th>Group</th>
<th>Average suturing time (sec): Session1</th>
<th>Average Suturing Time (sec): Session18</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-Haptics (n=10)</td>
<td>553.4 ± 447.9</td>
<td>86.5 ± 43.5</td>
<td>.001</td>
</tr>
<tr>
<td>Haptics (n=10)</td>
<td>465.5 ± 142.8</td>
<td>102.4 ± 55.3</td>
<td>.001</td>
</tr>
</tbody>
</table>

RESULTS

Learning curves

Individual learning curves were plotted using each subject’s average time to task completion per session from session 1 to session 18 (see Figure 2).

![Figure 2. The average time to task completion in each group per session. Error bars show the standard error.](image1)

Averaged suturing and knot-tying times for the first and last (18th) sessions are shown in Table 1. Performance in session 1 was significantly different from session 18 for both groups (Haptics group, F(17, 1243) = 38.8, p < .001; No-Haptics group, F(17, 1243) = 65.2, p < .001). There were significant differences between performance in session 1 and performance in all subsequent sessions in each group, suggesting that learning was occurring in the first session. The performance differences between sessions one to six and the last session are also shown in Table 1. There were significant performance differences between sessions 1-5 and the last session (session 18) in the No-Haptics group, while significant differences in performance were found only between sessions 1-4 and the last session in the Haptics group. The No-Haptics group reached the performance plateau by the 6th session, while the Haptics group reached the plateau by the 5th session.

Time to task completion

Time to task completion in the Haptics group was significantly faster than in the No-Haptics group over the 18 sessions, t(1243) = -7.2, p < .001. Pair-wise analysis of individual learning curves also showed a significantly faster time to task completion in the Haptics condition across the 18 training sessions, t(179) = -2.1, p < .04.

For every knot completed in training (the largest number of knots performed by a subject was 618, the average number was 200), subjects in the Haptics condition performed significantly faster than those in the No-Haptics condition, t(1405) = -11.7, p < 0.001 (see Figure 3, only the first 182 knots are shown in the graph). The best trial in each session for subjects in the Haptics condition was also significantly faster than that in the No-Haptics condition, t(179) = -2.8, p < 0.006 (see Figure 4).

![Figure 3. The average time to task completion in each group for the first 182 knots.](image2)

Performance variance

The variance of task completion time per session in the No-Haptics conditions was significantly higher than that in the Haptics condition, t(163) = 2.2, p < 0.03 (see Figure 5). Between subject variance for the first 182 knots completed during training in the No-Haptics condition was also significantly higher than that in the Haptics condition, t(166) = 3.0, p < 0.003 (see Figure 6).
Figure 5. The variance in time to task completion in each group per session.

Figure 6. The between subjects variance in time to task completion in each group for the first 182 knots.

**DISCUSSION**

Haptic feedback was shown to improve performance time during laparoscopic suturing and knot-tying training in our experiment, but only for the first five hours of training. One approach to measure learning is to look at the variability of the performance; decreasing variability indicates that the skill is being learned and thus performance becomes more consistent. In this experiment, haptic feedback allows trainees to perform more consistently in the initial stages of learning, and with a shorter learning curve. However, our learning curve results also suggest that the benefits of haptics in the latter stages of learning are minimal.

Note from Figure 5 that subjects took advantage of haptics at the very beginning of the learning, especially in the first two training sessions. However, in subsequent sessions, the learning curves of the Haptics and No-Haptics groups converge. This may be due to the fact that after initial familiarization with the instrumentation and task demands, where haptic feedback is beneficial, subjects have to concentrate on practicing the motor skills of suturing and knot-tying which require predominantly the coordination of hand gestures and tool movements. Suturing and knot-tying is a complex surgical task, requiring accurate positioning and controlling of instruments, needle, suture and tissue. Several key movements and gestures are involved in performing a successful suturing and knot-tying task, including positioning the needle to bite the tissue, rotating the needle driver to form the loop, and tightening the knot. As observed in this experiment, subjects seemed to rely mainly on visual feedback to position the needle to bite the tissue at the correct spot, and to manipulate the two needle drivers to form the loop. Furthermore, subjects in the Haptics group often relied on visual feedback to confirm that the knot was tight enough instead of relying on their haptic feedback alone. A previous study also suggested that haptic information perceived by the operator only serves to disorient when learning complex surgical tasks where gestures are more important (Picod et al, 2005). Suturing and knot-tying is a task that is more about orientation, positioning, movements, and gestures of instruments and suturing materials, than it is about controlling the force application and differentiation of tissue compliance. It seems that the performance of suturing and knot-tying were not affected dramatically by providing haptic feedback.

Although the benefits of haptics in the early stages of learning are subtle, those who learned with haptics were more consistent in performance, and had a shorter learning curve. Conversely, trainees who trained without haptic feedback experienced less performance consistency during the first several training sessions. There were also significant differences ($t(179) = 6.419, p < 0.001$) in the number of knots performed in each session by the two groups. It might be worth the additional costs to equip laparoscopic surgery simulators with haptic feedback, provided that consistent performance is important during initial training, or that limited time for training is available. The latter is an important consideration given the current restrictions on training time and working hours for residents. With haptic feedback, the training simulator presents more realism that allows the trainees to be more comfortable with initial practice, and results in faster performance stability in training. However, the effort and financial investment of implementing haptic feedback capabilities into surgical simulators are high and may not be justified by such subtle benefits.

Several questions arise based on our findings. For example, how do novice trainees benefit from haptic feedback at the very beginning of the training? Studies have shown that cognitive, perceptual, and motor demands comprise of three components in human skills training (Philbin, Ribarsky, Walker, & Hubbard, 1998). The cognitive component consists primarily of the construction of an internal model of the task within the trainee’s memory. In laparoscopic suturing and knot-tying, the trainee gradually learns where the needle and suture should go and how to make the loop with both instruments, and develops a strategy for completing a successful suture. The perceptual component of training enables the trainee to comprehend the environment (Adams et al, 2001). The suturing materials and environments were perceived through the trainee’s senses. These include spatial characteristics such as shape, size, orientation, and physical properties such as rigidity, mass, and friction. The motor demands of the task concern the dexterous manipulation of the suturing materials. The trainee must learn how to handle the materials, move them within the environment and orient them, form the loop, and tighten the knot. Therefore, the benefits of
haptics may depend on the nature of the task. As observed in previous studies on tissue probing tasks where force application control is more important.

One of the limitations of this study is that a post-training evaluation on an independent operating platform was not conducted. This would have enabled us to examine the effect of haptic feedback on skill retention and the transfer of skills into the real OR environment.

CONCLUSION

In general, learning with haptics was significantly better than training without haptics for a laparoscopic suturing and knot-tying task, but only in the first 5 hours of training. Based on these results, haptic feedback may not be warranted in laparoscopic surgical trainers at all stages of training. The benefits of a shorter time to the first performance plateau and more consistent initial performance should be balanced with the cost of implementing haptic feedback in training simulators.

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REFERENCE


