2017 IEEE World Haptics Conference (WHC)
Fürstenfeldbruck (Munich), Germany
6–9 June 2017

# A Wrist-Squeezing Force-Feedback System for Robotic Surgery Training

Jeremy D. Brown[1], Joshua N. Fernandez[2], Sean P. Cohen[3], and Katherine J. Kuchenbecker[4]

***Abstract*— Over time, surgical trainees learn to compensate for the lack of haptic feedback in commercial robotic minimally invasive surgical systems. Incorporating touch cues into robotic surgery training could potentially shorten this learning process if the benefits of haptic feedback were sustained after it is removed. In this paper, we develop a wrist-squeezing haptic feedback system and evaluate whether it holds the potential to train novice da Vinci users to reduce the force they exert on a bimanual inanimate training task. Subjects were randomly divided into two groups according to a multiple baseline experimental design. Each of the ten participants moved a ring along a curved wire nine times while the haptic feedback was conditionally withheld, provided, and withheld again. The real-time tactile feedback of applied force magnitude significantly reduced the integral of the force produced by the da Vinci tools on the task materials, and this result remained even when the haptic feedback was removed. Overall, our findings suggest that wrist-squeezing force feedback can play an essential role in helping novice trainees learn to minimize the force they exert with a surgical robot.**

## I. INTRODUCTION

Robotic minimally invasive surgery (RMIS) is used in an increasing number of procedures in surgical specialties such as urology [1], gynecology [2], and general surgery [3]. Robotic platforms like the Intuitive Surgical da Vinci are capable of providing surgeons with enhanced visualization and increased dexterity over traditional minimally invasive approaches like laparoscopic surgery. Unfortunately, all FDA-approved commercially available robotic platforms lack support for rich haptic feedback.

This lack of haptic feedback somewhat limits the procedures that can be done robotically, as surgeons cannot feel how hard they are pulling a suture or tactilely localize occlusions within tissue. It therefore seems appropriate that the majority of the research from the haptics community has focused on developing commercially viable haptic feedback systems [4], [5], [6], [7]. While many creative ideas have been proposed, none have made it into the operating theater in a permanent FDA-approved capacity. Although the development of a viable solution is likely on the horizon, a more pressing question arises: what can be done in the interim to help novice robotic surgery trainees quickly gain the skills necessary to reach the proficiency of experts?

Arguably one of the most important aspects of RMIS training is learning how to safely operate the robot when handling delicate tissue. Given current technology, novice surgical robotic trainees do not have direct access to the important haptic signals that govern such interactions. Previous work has demonstrated that tactile feedback in telesurgical and telerobotic platforms more broadly helps operators reduce their grip force [7], [8], contact forces and accelerations [9], and normal force [10]. Haptic feedback has also been shown to speed up the learning process in laparoscopic surgery [11]. Providing full three-dimensional force feedback during training would likely have similar results, but it is technologically challenging due to stability requirements and could not be used during surgeries on humans. Thus, an important objective for training solutions is ensuring that the performance improvement evoked by the haptic feedback persists even after the feedback is removed.

Expert robotic surgeons often claim to be able to "feel with their eyes." One possible goal for a haptic training system would thus be to help trainee surgeons learn to connect what they see with what they feel. This concept has been demonstrated previously for a force recall task [12], which suggests that a similar possibility might exist for surgery.

Simultaneously, it is worth considering that no standardized training curriculum exists yet for RMIS, unlike other approaches such as laparoscopic surgery. Current training often uses virtual reality (VR), structured inanimate tasks with the clinical robot, and *in vivo* and *ex vivo* animal models with the clinical robot. While VR training has been shown to correlate well with inanimate and *in vivo* training [13], training with a clinical robot is still considered the gold standard [14], [13]. Structured inanimate tasks are well suited for teaching many of the fundamental psychomotor skills such as tool manipulation, and their performance has been shown to correlate highly with *in vivo* training [13].

In this paper we seek to test the hypotheses that *providing users with real-time tactile feedback of the force they are exerting on an inanimate training task will assist them in producing less force* and that *this improvement in performance will be sustained even after the haptic feedback is removed*. To that end we developed and evaluated a wrist-squeezing force-feedback system that allows the user to feel the magnitude of the force they are producing with the

[1]J. D. Brown was with the Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104, USA when this work was conducted. He is now with the Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD 21218, USA jdelainebrown@jhu.edu

[2]J. N. Fernandez is with the Department of Mechanical Engineering, University of Maryland Baltimore County, Baltimore, MD 21250, USA fe5@umbc.edu

[3]S. P. Cohen is with the Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104, USA seanco@seas.upenn.edu

[4]K. J. Kuchenbecker is with the Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, PA 19104, USA and with the Haptic Intelligence Department, Max Planck Institute for Intelligent Systems, Stuttgart, Germany kjk@is.mpg.de

978-1-5090-1425-5/17/$31.00 ©2017 IEEE

robot. This haptic feedback was selectively provided and withdrawn at staggered points in the experiment to enable us to disambiguate natural learning from the performance changes induced by the feedback. While haptic feedback has been shown to improve learning in other applications, this paper presents the first known demonstration of the specific utility of haptic feedback to reduce the force trainees apply with the surgical robot.

## II. Methods

As explained in the following three subsections, we created a system that squeezes a trainee's wrists to tactilely convey the magnitude of the force vector he or she is applying with a surgical robot, evaluated this system's effects on naive users through a within-subjects experiment, and prepared to statistically analyze the task performance metrics and questionnaire data gathered during the study.

### A. Experimental Setup

Our experimental apparatus consisted of an Intuitive Surgical da Vinci Standard teleoperated surgical robot augmented with a custom tactile force-feedback system. We designed the feedback system to produce a squeezing stimulus on the user's wrists in proportion to the magnitude of the force vector being applied to the task materials by the da Vinci surgical tools. The haptic feedback system consists of a task platform containing a three-axis force sensor, two identical tactile actuators that squeeze the operator's wrists, a custom signal conditioning box, and an Intel NUC computer for data acquisition and control.

The task platform is a custom acrylic base that fits in the bottom of the white da Vinci skills dome; it was initially developed for automatically rating surgeon skill [15] and was then adapted for use in this project. A raised platform is mounted on a three-axis force/torque sensor (ATI Mini40 SI-40-2). The top plate of the platform features dowel pins and magnets to hold the task materials in a consistent location. The force sensor signal conditioning box is paired with a custom data acquisition board that features six differential analog inputs and nine single-ended analog inputs. This board is controlled by a Teensy 3.1 micro controller (32-bit ARM Cortex microprocessor) and contains chipsets for filtering, buffering, and analog-to-digital conversion.

The wearable tactile actuators are based on the Squeezer device developed by Stanley and Kuchenbecker [16], who found that users rated this design highly for intuitively conveying the magnitude of a stimulus [17]. Each one is composed of a 3D-printed mount that holds a position-controlled Futaba s3114 servo motor, which has a maximum output torque of 0.17 Nm. The device is secured around the user's wrist with a hook-and-loop strap, and a separate 3D-printed attachment rigidly secures one end of the strap to the servo horn. The range of motion of each servo is 50°; increasing the servo angle tightens the strap on the user's wrist. Control for the servos was provided by a PhidgetAdvancedServo 8-motor (1061_0) servo driver, which was powered by a bench-top power supply at 6 V. In operation, the angle commanded to each of the servos was set as follows:

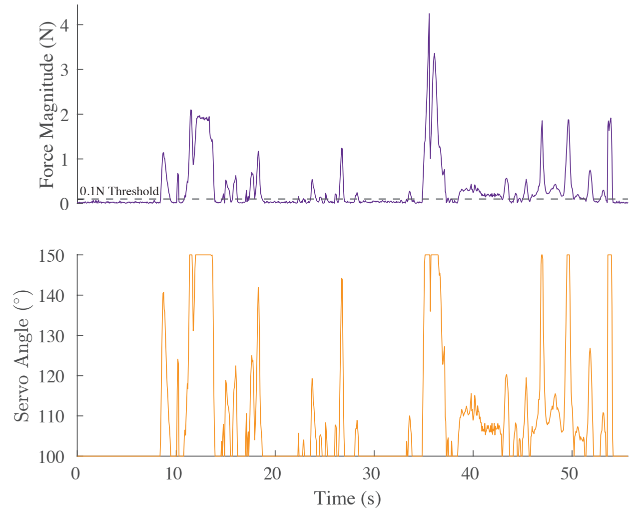


Fig. 1. Sample force magnitude and commanded servo angle signals for one trial by a representative participant. The dashed line shows the 0.1 N level at which the force magnitude was thresholded when modulating the servo angle. Both tactile actuators receive the same command.

$$\Theta_{\text{cmd}} = \begin{cases} \Theta_{\text{min}} & \text{if } F_{\text{mag}} < F_{\text{thresh}} \\ \Theta_{\text{min}} + \gamma F_{\text{mag}} \left( \Theta_{\text{max}} - \Theta_{\text{min}} \right) & \text{otherwise} \end{cases} \tag{1}$$

where $\Theta_{\text{cmd}}$ is the angle commanded to the tactile actuator's servo, $\Theta_{\text{min}} = 100°$ is the servo's minimum allowed angle, $\Theta_{\text{max}} = 150°$ is the servo's maximum allowed angle, $F_{\text{mag}}$ is the time-varying magnitude of the three-axis force vector measured by the force sensor, $F_{\text{thresh}}$ is a threshold for detecting non-zero force magnitude, and $\gamma$ is a gain that adjusts the sensitivity of the feedback. Pilot testing was used to explore different threshold and gain values; the reported experiment used $F_{\text{thresh}} = 0.1\,\text{N}$ and $\gamma = 0.714\,\text{N}^{-1}$. The output $\Theta_{\text{cmd}}$ is also clamped between $\Theta_{\text{min}}$ and $\Theta_{\text{max}}$ using conditional statements. Fig. 1 shows a sample time history of $F_{\text{mag}}$ and $\Theta_{\text{cmd}}$ from the reported study.

The data acquisition board and the PhidgetAdvancedServo servo driver were both connected to the Intel NUC computer via USB. The entire data recording and servo control process was handled through a Python script running at about 16.7 Hz. This script also zeroed the force sensor before each trial. The user started and stopped the recording process using a foot pedal, so that he or she could already be holding the da Vinci master hand controllers when the trial started. A strip of LEDs mounted above the robot view port indicated the current recording status to the user.

### B. Experimental Protocol

We tested $N = 12$ participants (11 male, one female, mean age 26±7 years) from the general population of the University of Pennsylvania. Subjects were compensated with a \$20 gift card. All study procedures were approved by our Institutional Review Board under protocol #825932. The experimental protocol followed a multiple-baseline design in which baseline measures of performance were taken before

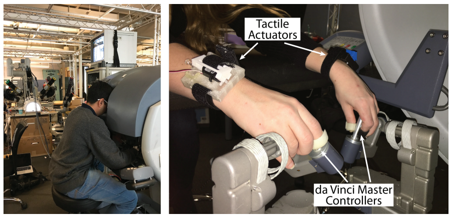


Fig. 2. Experimental setup: The participant sits at the da Vinci console to perform the task and wears identical tactile actuators on the two wrists.

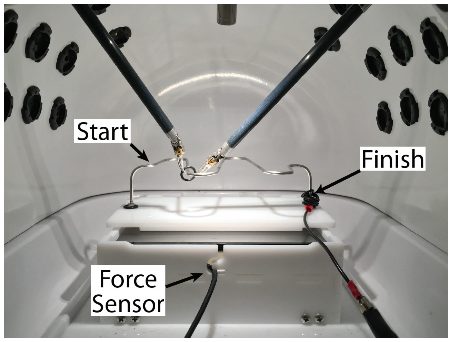


Fig. 3. Ring rollercoaster task mounted on top of the task platform with embedded three-axis force sensor. One ring was placed at the start location for each trial.

haptic feedback was introduced and after it was removed. The introduction of haptic feedback was also staggered between two groups of participants to minimize the impact of natural learning and fatigue in the outcome measures [18].

After giving informed consent, the participant was randomized into group A or B. He or she then completed a demographic questionnaire and sat at the da Vinci surgeon's console as shown in Fig. 2. The experimenter explained the da Vinci system, including how to adjust the ergonomics, focus the camera, and clutch the tools and camera. The participant spent three minutes practicing grasping and manipulating objects with the surgical tools. Then the experimenter took the participant through a guided practice task to ensure they understood how to effectively move the surgical camera and tools around the entire workspace. After the practice session, the tactile actuators were placed on the participant's wrists, and the participant tested the tactile force-feedback system to understand how it works. The participant was shown how to operate the data recording system using the foot pedal and light strip. He or she then viewed static images depicting the ring rollercoaster task described below, which was chosen as a challenging eye-hand dexterity task from the Intuitive Surgical da Vinci Skills Drill Practicum.

*a) Ring Rollercoaster Task:* The rings begin on the left-hand side of the curved wire, as shown in Fig. 3. Starting with the left surgical tool, the participant picks up one ring and moves it along the wire from left to right to the finish position, transferring from hand to hand as needed. Participants were told to complete the task *as quickly as possible while trying to minimize the forces they produced on the task board*. Furthermore, they were instructed not to drop the ring and to move the camera to keep the ring and both tools in the center of the view.

Participants completed nine trials of the ring rollercoaster

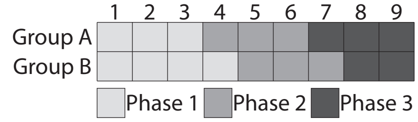


Fig. 4. Experimental protocol schematic highlighting how groups A and B changed phases for trials 1-9. In phase one and three, the haptic feedback system was not active. In phase two, the haptic feedback system was active. In the phase three, the haptic feedback system was inactive.

task in the sequence shown in Fig. 4. The trials were grouped into three phases. In phase one, the haptic feedback system was turned off. In phase two, the haptic feedback system was turned on, and in phase three the haptic feedback system was turned off again. For the participants in group A, the transitions between the phases occurred after the third and six trials, while the transitions occurred after the fourth and seventh trials for the participants in group B.

Participants wore the tactile actuators for all nine trials, regardless of whether the haptic feedback system was active. Before participants began each trial, the tools were reloaded to reset their configuration, and the camera was adjusted to give a global view of the task board and the tool tips. After each phase, participants completed a questionnaire that contained quantitative and qualitative questions about their experience performing the task in that particular phase.

### C. Metrics and Data Analysis

Our primary performance metrics were the integral of the force magnitude vector and the trial duration. The force integral shows the total force the subject applied to the task board and was computed using the `trapz` function in Matlab. Trial duration shows how quickly the subject performed the task and was taken as the time elapsed between the starting and ending pedal presses. One participant forgot to press the pedal at the end of the first trial; this trial duration and force integral were calculated using the video recorded from the robot camera.

*1) Post-Phase Questionnaires:* A separate questionnaire was given to participants after each phase of the experiment. The first six questions were taken from the NASA-TLX survey [19], and the others focused on the subject's more nuanced perception of their performance. Phases two and three included additional questions about the effects of the presence or absence of the tactile feedback. Participants responded to each question on a sliding scale from 0 to 100 and also had the option of entering explanatory text. For the first twelve questions, only the responses for which a significant difference was found between phases or groups will be discussed further.

*2) Statistical Analysis:* All statistical analyses were performed using R (v.3.3.2). A multilevel linear model was used to assess the effect of experiment phase and participant group on each of the two primary performance metrics and all twelve of the sliding-scale questions that were asked after every set. Within each model, participant was a random effect, experiment phase was a repeated-measure predictor, and group was a between-subject predictor. We determine significance using $\alpha = 0.05$.

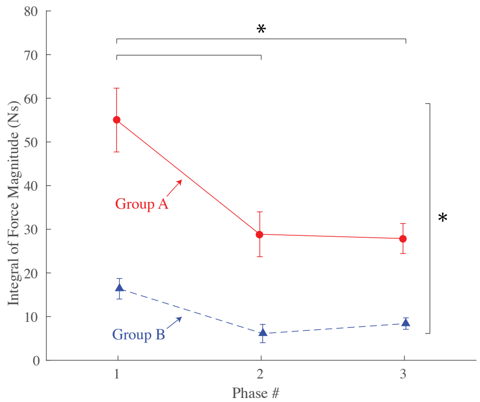


Fig. 5. Mean force integral for all participants in each experiment phase. The solid red lines indicate group A, while the dashed blue lines are for group B. The error bars show the standard error of the mean.

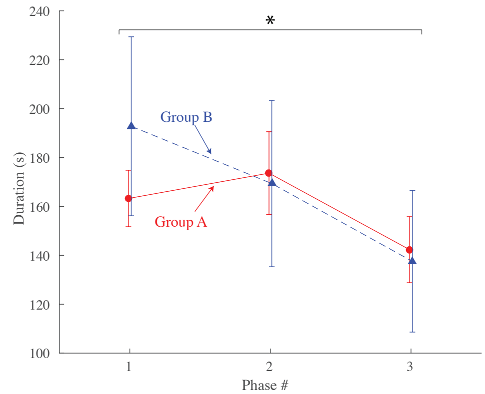


Fig. 6. Mean trial duration for all participants in each experiment phase. The solid red lines highlight the participants in group A. The dashed blue lines highlight the participants in group B. The error bars represent $\pm 1$ standard error of the mean.

## III. Results

One subject did not receive consistent instructions on how to perform the task, so their data have been removed from analysis. Additionally, another participant handled the robot so roughly that they pulled the ring rollercoaster task off the task platform during the first trial. Given that this startling event may have biased how that participant performed during the rest of the experiment, this individual's data have also been omitted. Our results therefore focus on the remaining 10 participants, which included five participants in each group.

### A. Force Integral

Fig. 5 shows the mean force integral for participants in groups A and B across the three phases of the experiment. Each participant's values were averaged across the relevant trials before analysis. We found significant main effects of the experiment phase ($\chi^2(2) = 15.11$, $p < 0.001$) and the group to which participants belonged ($\chi^2(1) = 21.44$, $p < 0.0001$) on the integral of the force magnitude vector. Contrasts were used to break down the main effects of phase. The first contrast revealed a significant difference between the force integrals between phases one and two ($b = -26$, $t(16) = -4.48$, $p = 0.004$, $r = 0.75$). The second contrast revealed a significant difference between the force integrals between phases one and three ($b = -27$, $t(16) = -4.64$, $p = 0.003$, $r = 0.76$). The third contrast revealed that the difference between the force integrals in phases two and three was not significant ($b = -0.9$, $t(16) = -0.16$, $p = 0.87$, $r = 0.04$). Contrasts were also used to break down the main effects of group. The contrast revealed a significant difference between the force integrals for participants in group B and group A ($b = -23$, $t(8) = -3.88$, $p = 0.005$, $r = 0.81$). No other significant contrasts or interaction effects were found.

### B. Trial Duration

Fig. 6 shows the mean trial duration for groups A and B for all three phases of the experiment. We found a significant main effect of the experiment phase ($\chi^2(2) = 8.61$, $p = 0.013$). There was no significant main effect for participant group ($\chi^2(1) = 0.05$, $p = 0.82$). No other significant interaction effects or contrasts were found.

### C. Survey

Fig. 7 shows the mean responses for questions that showed any significant affects. Q3 ("How hurried or rushed was the pace of the task?") had significant main effects of experiment phase ($\chi^2 = 15.74$, $p < 0.001$) and participant group ($\chi^2 = 11.09$, $p < 0.001$). Contrasts revealed a significant difference in response between phases one and three ($b = 11$, $t(16) = 2.59$, $p = 0.02$, $r = 0.54$), and a significant difference in response between group B and group A ($b = 21$, $t(8) = 2.88$, $p = 0.02$, $r = 0.71$).

Q4 ("How successful were you at accomplishing what you were asked to do?") had a significant main effect of participant group ($\chi^2 = 4.7$, $p = 0.03$). There were no significant contrasts for Q4.

Q6 ("How insecure, discouraged, irritated, stressed, and annoyed were you?") showed a significant main effect of participant group ($\chi^2 = 5.7$, $p = 0.02$). There were no significant contrasts for Q6.

Q7 ("How successful were you in performing the task as gently as possible?") had a significant interaction of experiment phase and participant group ($\chi^2 = 7.45$, $p = 0.02$). Contrasts revealed a significant difference in response between phases one and two for participants in group B ($b = 28$, $t(16) = 2.53$, $p = 0.02$, $r = 0.53$).

Q8 ("How successful were you in performing the the task as quickly as possible?") had a significant main effect of experiment phase ($\chi^2 = 10.19$, $p = 0.006$), but there were no significant contrasts for Q8.

Q11 ("How well could you concentrate on the assigned task?") had a significant main effect of experiment phase ($\chi^2 = 8.73$, $p = 0.01$) with no significant contrasts.

In regard to the questions that subjects answered only once, participants on average thought that the haptic feedback system involved them (Q13, $\overline{x} = 73.2$ out of 100, $\sigma_{\overline{x}} = 7.3$), that the haptic feedback in phase two moderately affected their performance in phase three (Q14, $\overline{x} = 64.8$, $\sigma_{\overline{x}} = 8.6$), and that the lack of haptic feedback in phase three slightly affected their performance (Q15, $\overline{x} = 58.9$, $\sigma_{\overline{x}} = 7.0$).

The other survey questions for which there were no significant differences were: Q1 ("How mentally demanding

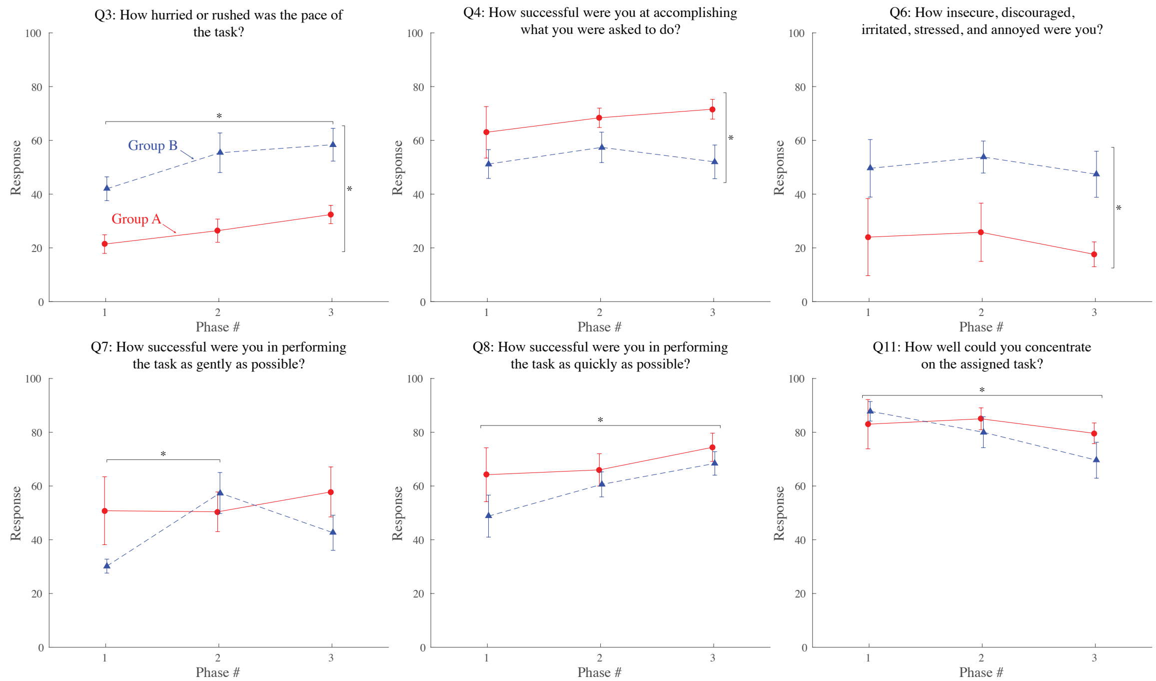


Fig. 7. Mean questionnaire responses for all participants in each experiment phase. The solid red lines highlight the participants in group A, while the dashed blue lines highlight those in group B. The error bars represent $\pm1$ standard error of the mean.

was the task?"), Q2 ("How physically demanding was the task?"), Q5 ("How hard did you have to work to accomplish your level of performance?"), Q9 ("How natural was your manipulation of the tools?"), Q10 ("How much did the visual aspects of the task involve you?"), and Q12 ("How would you rate your overall situational awareness?")

## IV. Discussion

This study sought to determine whether a tactile force-feedback system can help users of a surgical robot reduce the forces they exert when performing a bimanual training task, as well as whether any reduction in force persists when the feedback is no longer available. Our system measures the magnitude of the force vector produced by the da Vinci surgical tools on the ring rollercoaster task and displays it as a squeezing stimulus on the operator's wrists through servo-driven tactile actuators. The ten participants were broken into two groups with staggered transitions between the study phases with and without haptic feedback to help account for any effects caused by trial number, such as natural learning.

Overall, our findings indicate that wrist-squeezing force feedback is an effective tool for teaching trainees to produce smaller forces with a surgical robot. When available, the addition of haptic feedback helped participants significantly reduce the force integral they were producing compared to initial trials without haptic feedback. Because this large effect was seen in both participant groups, it can be argued that it was due the availability of haptic feedback. Additional results for both groups demonstrated that when the haptic feedback was removed, participants produced a force integral that was on average significantly lower than the force integral in the phase one trials (no feedback), and was on average *not* significantly different from the phase two trials where haptic feedback was available. The survey responses show that participants were definitely aware of the wrist-squeezing feedback and felt it had a benefit, even after it was removed.

This last finding is promising because commercially available robotic surgery platforms do not provide haptic feedback. Although systems like ours cannot providing intraoperative haptic feedback, they hold potential for enhancing the robotic surgery training process. Expert robotic surgeons must rely heavily on vision to estimate the forces they are producing with the robot. While this skill develops naturally with repeated practice, we have demonstrated that a tactile force-feedback system can greatly accelerate that learning process. By providing trainees with real-time feedback of their exerted forces, the system seems to help them learn to to look for and avoid undesirable haptic sensations.

We also determined that the phase of the experiment, and thus the availability of haptic feedback, had an effect on the time participants took to finish each trial. Participants in group B appear to have started at a slower pace than participants in group A. The introduction of haptic feedback in phase two had a differing but equalizing effect on both participant groups. The availability of haptic feedback seems to have helped group B perform the task faster, a trend that remained even after the haptic feedback was removed. The availability of haptic feedback had a more disruptive effect on the speedier participants of group A, making them slow down somewhat and then speed up again when it was removed.

The difference in approach between the two groups is also supported by the force integral results. Group B produced significantly lower forces than group A throughout the experiment. The introduction of haptic feedback showed group

B that their forces were low and enabled them to reduce their forces even further; thus they appeared to gain some confidence in performing the task faster. For participants in group A, the converse was more likely; the haptic feedback made these participants aware of how much force they were producing, thus causing them to slow down and try to perform the task more gently. Guiding trainees toward a single desired strategy could be highly useful.

The survey results revealed additional differences between the two groups. Compared to group A, group B felt the task was more hurried and rushed, felt they were less successful at accomplishing the task objectives, and felt more insecure, discouraged, irritated, stressed, and annoyed during the experiment. Yet the metrics clearly show that group B performed the task more gently and with the same speed as group A. Participants in group B felt that they were more gentle after having received haptic feedback, a sentiment that group A participants did not share. When looking at the demographics of the participants, indicators that could potentially justify these differences are differences in age (group A: 23$\pm$2 years, group B: 31$\pm$9 years), profession (all participants in group A were students, while two participants in group B were professionals and the rest were students), and familiarity with video games (all participants in group A selected 3-moderate while one participant in group B selected 2-limited, two participants selected 3-moderate, and two participants selected 4-extensive). Our randomization into groups did not account for age, profession, or video game experience, and these factors may have played some role in the way participants approached the task. Still, it seems likely that some factor other than age, profession, or video game experience accounts for the differences between the two groups, especially in terms of the forces produced. All participants were given experimental instructions before being assigned a group and were never explicitly told which group they belonged to. In addition, there were no differences between groups in the time of day at which the experiment was performed. While our survey results highlight potential intrinsic differences between participants in the two groups, a definitive understanding of what caused these performance differences remains unknown.

While we demonstrated the potential benefits of a haptic feedback system for robotic surgery training, a few limitations need to be considered. First, we were able to analyze the results from only ten participants who were not surgical trainees. Testing individuals with more experience and prior exposure to robotic surgical platforms might affect the outcomes. Additionally, testing more participants would validate whether the observed between-group differences remain, or if they are symptomatic of a small sample size. Finally, we studied only one particular training task that requires complex dexterous motion along a stiff constraint; the effects of the feedback will likely depend on the task.

Despite these limitations, our results highlight that tactile feedback of contact force magnitude can have both an immediate and a persistent impact on a trainee's performance even after the feedback has been removed, supporting the idea that trainees can learn to "feel with their eyes."

## References


[1] K. K. Badani, S. Kaul, and M. Menon, "Evolution of robotic radical prostatectomy," *Cancer*, vol. 110, no. 9, pp. 1951–1958, 2007.

[2] A. L. Smith, K. M. Schneider, and P. D. Berens, "Survey of obstetrics and gynecology residents' training and opinions on robotic surgery," *Journal of Robotic Surgery*, vol. 4, no. 1, pp. 23–27, 2010.

[3] S. Maeso, M. Reza, J. A. Mayol, J. A. Blasco, M. Guerra, E. Andradas, and M. N. Plana, "Efficacy of the da Vinci surgical system in abdominal surgery compared with that of laparoscopy: a systematic review and meta-analysis." *Annals of Surgery*, vol. 252, no. 2, pp. 254–262, 2010.

[4] K. Bark, W. McMahan, A. Remington, J. Gewirtz, A. Wedmid, D. I. Lee, and K. J. Kuchenbecker, "In vivo validation of a system for haptic feedback of tool vibrations in robotic surgery." *Surgical Endoscopy and Other Interventional Techniques*, vol. 27, no. 2, pp. 656–64, 2013.

[5] A. M. Okamura, "Haptic Feedback in Robot-Assisted Minimally Invasive Surgery," *Current Opinion in Urology*, vol. 19, no. 1, pp. 102–107, 2009.

[6] L. Meli, C. Pacchierotti, and D. Prattichizzo, "Sensory subtraction in robot-assisted surgery: fingertip skin deformation feedback to ensure safety and improve transparency in bimanual haptic interaction." *IEEE Transactions on Biomedical Engineering*, vol. 61, no. 4, pp. 1318–27, 2014.

[7] C.-h. King, M. O. Culjat, M. L. Franco, J. W. Bisley, G. P. Carman, E. P. Dutson, and W. S. Grundfest, "A Multielement Tactile Feedback System for Robot-Assisted Minimally Invasive Surgery," *IEEE Transactions on Haptics*, vol. 2, no. 1, pp. 52–56, 2009.

[8] C.-h. King, M. O. Culjat, M. L. Franco, C. E. Lewis, E. P. Dutson, W. S. Grundfest, and J. W. Bisley, "Tactile Feedback Induces Reduced Grasping Force in Robot-Assisted Surgery," *IEEE Transactions on Haptics*, vol. 2, no. 2, pp. 103–110, 2009.

[9] R. P. Khurshid, N. T. Fitter, E. A. Fedalei, and K. J. Kuchenbecker, "Effects of Grip-Force, Contact, and Acceleration Feedback on a Teleoperated Pick-and-Place Task," *IEEE Transactions on Haptics*, vol. 10, no. 1, pp. 40–53, 2017.

[10] C. R. Wagner, N. Stylopoulos, and R. D. Howe, "The role of force feedback in surgery: Analysis of blunt dissection," in *Proc.10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2002, pp. 68–74.

[11] M. Zhou, S. Tse, A. Derevianko, D. B. Jones, S. D. Schwaitzberg, and C. G. L. Cao, "Effect of haptic feedback in laparoscopic surgery skill acquisition," *Surgical Endoscopy and Other Interventional Techniques*, vol. 26, no. 4, pp. 1128–1134, 2012.

[12] D. Morris, T. Hong, F. Barbagli, T. Chang, and K. Salisbury, "Haptic feedback enhances force skill learning," in *Proc. Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2007, pp. 21–26.

[13] A. J. Hung, I. S. Jayaratna, K. Teruya, M. M. Desai, I. S. Gill, and A. C. Goh, "Comparative assessment of three standardized robotic surgery training methods," *BJU International*, vol. 112, no. 6, pp. 864–871, 2013.

[14] R. Korets, A. C. Mues, J. a. Graversen, M. Gupta, M. C. Benson, K. L. Cooper, J. Landman, and K. K. Badani, "Validating the use of the Mimic dV-trainer for robotic surgery skill acquisition among urology residents," *The Journal of Urology*, vol. 78, no. 6, pp. 1326–1330, 2011.

[15] J. D. Brown, C. E. O'Brien, S. C. Leung, K. R. Dumon, D. I. Lee, and K. J. Kuchenbecker, "Using Contact Forces and Robot Arm Accelerations to Automatically Rate Surgeon Skill at Peg Transfer," *IEEE Transactions on Biomedical Engineering*, vol. PP, no. 99, 2016.

[16] A. A. Stanley and K. J. Kuchenbecker, "Design of body-grounded tactile actuators for playback of human physical contact," in *Proc. IEEE World Haptics Conference*, 2011, pp. 563–568.

[17] ——, "Evaluation of tactile feedback methods for wrist rotation guidance," *IEEE Transactions on Haptics*, vol. 5, no. 3, pp. 240–251, 2012.

[18] I. Bulté and P. Onghena, "Randomization tests for multiple-baseline designs: an extension of the SCRT-R package." *Behavior Research Methods*, vol. 41, no. 2, pp. 477–485, 2009.

[19] S. G. Hart and L. E. Staveland, "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," *Advances in Psychology*, vol. 52, no. C, pp. 139–183, 1988.