Tool Vibration Feedback May Help Expert Robotic Surgeons Apply Less Force During Manipulation Tasks

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INTRODUCTION

Teleoperated robotic surgery systems can provide naturalistic hand-to-tool motion mappings and high-definition stereoscopic visuals; however, surgeons [1-2] and engineers [3-4] recognize that the lack of touch feedback provided to the operator remains a major limitation of these devices. Without effective haptic cues, the surgeon must rely on vision to guide their interactions with the surgical environment, a practice that may lead to increased cognitive load, error incidence, and tissue trauma. Although various haptic interfaces have been developed for robotic minimally invasive surgery, researchers have only recently begun to evaluate the influence of haptic feedback on task performance. Here, we present results from a set of in vitro tasks done by Dr. David I. Lee, an expert urologic surgeon who has performed over 2500 da Vinci procedures on human patients. The aim of the study was to explore the potential clinical impact of VerroTouch, a haptic and auditory tool vibration feedback system recently developed by our group [5].

MATERIALS AND METHODS

This IRB-approved study included three in vitro manipulation tasks: peg transfer, passing a suture needle through holes in a vertical plastic sheet, and suturing a laceration in simulated tissue. Subjects used an Intuitive da Vinci S robot to perform each task under four sensory feedback conditions: visual only (V), visual with audio (VA), visual with haptic (VH), and visual with audio and haptic (VAH), where visual signifies the da Vinci's stereoscopic camera. Audio and haptic indicate the two modes of tool vibration feedback available from VerroTouch. The presentation order of the feedback conditions was randomized by subject. Dr. Lee experienced the conditions in the following order: VA, VH, VAH, V. Subjects were instructed to complete the tasks quickly, accurately, and with minimal force.

The da Vinci robot used in this study was augmented with the tool vibration feedback system described in [5]. It consists of basic modules that can be quickly attached to a surgical robot without permanent modifications. As shown in Fig. 1, a low-cost three-axis accelerometer is mounted on each patient-side manipulator just below the interchangeable tool mounting point. This location within the robot's sterile drapes eliminates the need for

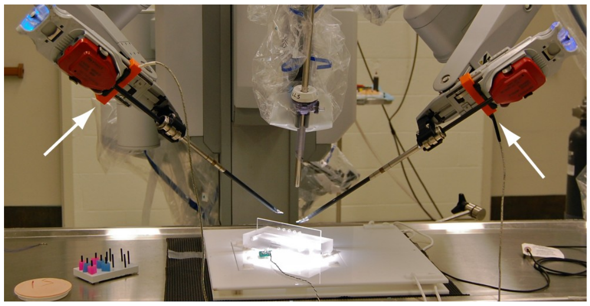

Fig. 1. A da Vinci S robot augmented with tool vibration sensors (arrows). Task materials are mounted to the white board, which is instrumented with a force sensor.

sensor sterilization, a common hurdle for haptic feedback in medical robotics. The measured acceleration signals are band-pass filtered from 80 to 1000 Hz and amplified to drive the outputs. Stereo speakers mounted to the sides of the surgeon console provide auditory feedback, and voice coil actuators mounted near the surgeon's hands generate vibrotactile haptic feedback. High-frequency accelerations experienced by the left or right tools are displayed to the surgeon via the corresponding speaker and actuator. The vibrations provided by this system are similar to what a surgeon could hear and feel if they were directly manipulating the instruments, though low-frequency forces and torques are not transmitted.

A time history of the tool accelerations and contact forces that occurred was recorded during each trial. Forces were measured by mounting the task materials to a white acrylic board that was instrumented with an ATI Mini40 force-torque sensor, as seen in Fig. 1. To reduce data dimensionality, we calculated the root-mean-square (RMS) of the magnitude of the three-dimensional force vector when either instrument exerted a measurable force on the task materials.

RESULTS

In addition to the expert subject discussed here, the study included five attending surgeons and six surgical residents of varying specialty, none of which had prior exposure to VerroTouch. Only three of these surgeons had significant clinical experience with robotic surgery (from 150 to 800 operations). Results from these other eleven subjects are reported in a separate publication [6]. Fig. 2 shows how the RMS forces applied by Dr.

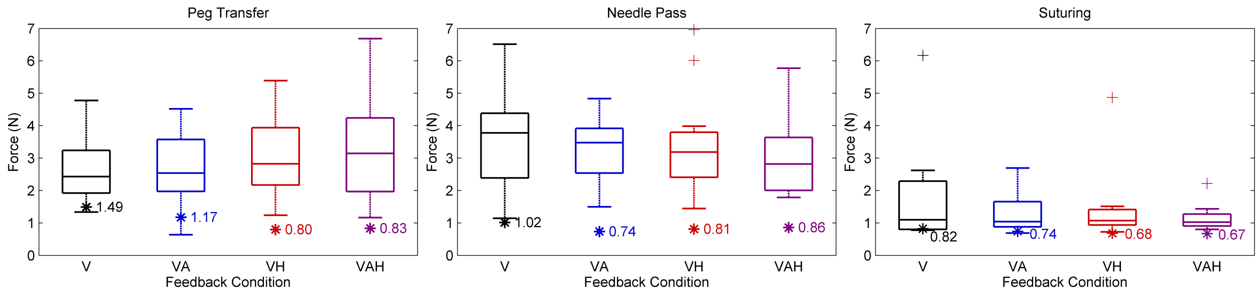

Fig. 2. Box plots of the RMS forces applied to the task materials by the eleven surgeons who participated in the study from [6]. The expert surgeon's performance, not included in the box plots, is overlaid with an asterisk.

Lee compare to the range of forces applied by the other subjects for each task and feedback condition. Additionally, Dr. Lee was among the quicker subjects to complete each trial, and often the quickest. His data have no discernible relationship between completion time and feedback condition.

We performed a within-subject analysis of variance of Dr. Lee's RMS force data, where the factors examined were auditory feedback (provided or absent), haptic feedback (provided or absent), and task (peg transfer, needle pass, or suturing). Taking $\alpha = 0.05$, this analysis shows that the presence of haptic feedback of tool vibrations ($F(1, 11) = 5.18$, $p = 0.057$, $\eta^2 = 0.24$) and task identity ($F(2, 11) = 4.34$, $p = 0.060$, $\eta^2 = 0.40$) approach significance, while audio feedback does not ($F(1, 11) = 1.07$, $p = 0.336$). The trend for haptic feedback did not hold for the population of less experienced subjects who participated in the study [6].

DISCUSSION

It is natural to expect that more experienced surgeons handle task materials efficiently and delicately. Our study quantifies efficiency and delicacy via task completion time and the RMS force applied to the task materials. The efficiency and delicacy of Dr. Lee's manipulations are evident when comparing his times and forces with those of less experienced surgeons. For many conditions, he achieved both the fastest time and the lowest forces. These findings suggest that one may be able to evaluate robotic surgery skill or experience by measuring the force a surgeon applies to in vitro task materials. We are in the process of analyzing the recorded tool accelerations to determine whether they may also be a potential candidate for assessing skill.

An analysis of variance of the force data suggests that the haptic tool vibration feedback provided by VerroTouch enabled Dr. Lee to apply less force to the task materials while still completing tasks quickly. Since the visual only (V) feedback condition was presented last, the performance improvement cannot be attributed to practicing the tasks. Given this subject's prior exposure to VerroTouch (approximately three hours total), this result suggests that surgeons can learn to use tool vibration feedback to interact more delicately with their environment.

While this trend was not generally replicated in the study reported in [6], the eleven other participants were naive to VerroTouch, and the majority had no experience with robotic surgery. We hypothesize that giving these subjects more time to practice with VerroTouch and the da Vinci would enable them learn to use the haptic tool vibration feedback to operate more delicately. These subjects also expressed a significant positive preference for the inclusion of tool vibration feedback [6], indicating that they believe it would be useful in a real operative setting.

In summary, analysis of an expert's RMS force data from in vitro tasks suggests that haptic tool vibration feedback may help experienced users reduce the forces they apply during manipulation tasks. Furthermore, we believe RMS force may be a useful metric for evaluating an individual's skill at robotic surgery.

ACKNOWLEDGMENTS

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