Assessment of Vibrotactile Feedback in a Needle-Insertion Task using a Surgical Robot

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ABSTRACT

The present study examined the effect of vibrotactile feedback in a needle-insertion task using a surgical robot. Four participants performed the task by hand (using a manual needle driver instrument) and by using a surgical robot, with or without vibrotactile feedback. The vibrotactile feedback signal indicated the deviation in force direction, with the signal amplitude modulated by the force magnitude. Visual feedback was always available in all experimental conditions. The participants' task was to insert a hooked needle into a simulated tissue pad at a pre-marked entrance point and drive it out of the tissue pad at a corresponding pre-marked exit point. The participants were instructed to hold the hooked needle in an orientation that minimized side-loading on the simulated tissue pad and prevented needle rotation in the needle driver. The forces exerted by the needle on the simulated tissue pad were recorded. The results indicated that the vibrotactile display was useful in reducing the overall force-direction deviation during the needle-insertion task, but it increased task completion time. It generally took twice as long to perform the task with the robot than with the hand. One participant who was experienced with the surgical robot consistently applied less force with the robot than with the hand. The vibrotactile feedback reduced the magnitude of the force component that was perpendicular to the suturing surface, but not the forces along the suturing surface. We compare our results to those reported in the literature and discuss the challenges we faced in assessing haptic feedback in a skilled surgical task such as the one used in the present study.

KEYWORDS: Surgical robot, surgical simulation, vibrotactile feedback, evaluation, needle-insertion task.

INDEX TERMS: H.5.2 [Information Interfaces and Presentation]: User Interfaces – Haptic I/O; H.1.2 [Models and Principles]: User/Machine Systems – Human factors.

1 INTRODUCTION

Surgical robotics is a fast-growing area that holds much promise for improved patient care. Commercially-available systems like the daVinci (Intuitive Surgical, Sunnyvale, CA) are now being used on a daily basis in hospitals and clinics. The general consensus is that teleoperated surgical robots can dramatically decrease trauma to tissues and muscles surrounding the diseased organs in a minimally-invasive surgery, thereby reducing complications and post-surgery recovery time. However, much debate exists on what role, if any, haptic feedback plays in a surgical robotic system.

In addition to assisting surgeons in the operating room, surgical robotic systems can also be used in a clinical training setting. By simulating a virtual patient, such tools can provide surgical residents with a virtual "hands-on" experience before they operate on real patients. A number of studies have assessed the utility of sensory feedback in such training systems (e.g., [1, 2]). One study found that force feedback can reduce the total force exerted by the user of a surgical robot on surrounding tissues while performing a blunt dissection [3, 4]. Visual feedback of haptic information has also been found to be generally useful [5]; for example, visual trajectory cue improved performance of unskilled users in a suturing task [6].

The benefits of haptic feedback in a skill training task is demonstrated by a study where users were able to operate a teleoperation system and judge the weight of objects held by the remote robot by feeling force information encoded redundantly through both the amplitude and frequency of vibrations on the fingertips [7]. Such benefits can sometimes be less clear-cut [8]. In general, performance with combined visual and haptic feedback is better than that with either visual or haptic feedback alone [9, 10].

Given the difficulty and high-cost associated with force sensing and force feedback in a surgical robotic system (although, see [11]), it appears attractive to consider alternative means of displaying the types of haptic information readily available to surgeons performing traditional, direct-contact surgery. Encouraged by previous results such as [4, 7], the present study was designed to assess the effect of vibrotactile feedback in a needle-insertion task using a surgical robot.

A common problem in surgical suturing is undesired needle rotation (deflection). This problem is especially prevalent on low-cost systems, such as the Laprotek (Endovia Medical, Norwood, MA) surgical robot, which uses disposable needle drivers and are unable to provide a high grip-strength due to compression of plastic components in the instrument. The needle rotation is usually caused by excessive tangential (to the tissue surface) forces on the needle by the tissue sample, either when inserting the needle in an incorrect direction or while continuing to drive the needle in a direction that deviates from the desired trajectory. Although a user can eventually detect the rotation of a needle in

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the instrument jaws from the visual image of the suturing needle without haptic feedback, it is difficult to detect the onset of needle rotation until it is too late.

The present study investigated the following question: Can the display of force-direction information through vibrotactile feedback reduce the amount of force-direction deviation during a needle-insertion task? We have chosen the single-handed needle-insertion component of a suturing task for our investigation in order to reduce the complexity associated with a typical suturing task that requires not only correct needle insertion but other skills such as two hand coordination. We hypothesized that with the needle-heading information provided by the vibrotactile feedback, a user will be better able to insert a needle along the correction direction. Our findings confirmed that the vibrotactile display was generally useful in reducing the overall drift during a needle-insertion task, but it also increased the task completion time.

2 METHODS

2.1 Apparatus

A Laprotek surgical robot (Endovia Medical, Norwood, MA) was used in the present study. The slave robot is comprised of two robotic arms with articulated elbow/wrist joints [12]. The master robot is comprised of a station with two manipulators corresponding to the two arms on the slave robot (Figure 1).

The low level motor controllers of Laprotek surgical system use servo rates of 2000 Hz, but the position update rate between the master and the slave is 100 Hz. The latter is fast enough to track the relatively slow motions used during surgery and maintains stability since the system does not implement force feedback. Similar to the daVinci system, the Laprotek robot uses tip-based control to transform the master motions into drive commands for the slave instruments. The slave instrument jaws therefore track the surgeon's fingertip positions and orientations. The orientations and angular motions (roll, pitch, yaw and angles) are tracked 1:1, and the position motions (X, Y, and Z translations) are scaled down 3:1. This means that the master handle translations are 3 times that of the slave instruments translations. This control scheme does provide a slightly different experience to the user during suturing. With standard handheld needle drivers, the instrument jaws are displaced from the hand by 50 to 75 mm. This extra "lever arm" may contribute toward better control of orientation angles during needle insertion.

For the present study, only one of the two arms was needed for a one-handed needle-insertion task. A Laprotek needle-driver instrument with carbide jaw surfaces was used to provide the maximum amount of grip on the Chromic gut SH-type suturing needle (Ethicon, Comelia, GA).

A standard video camera was placed behind the slave robot arms and was angled to provide a maximum unobstructed view of the suturing site (Figure 2). The video was shown on a monitor placed on top of the master robot directly in front of the participant (Figure 1). A curtain was used to obscure the slave robot and force-sensor assembly from the participant's view. Therefore, the visual display was the only means of visual feedback.

For comparison, the participants also performed the suturing task with a standard hand-held stainless-steel needle driver. The needle driver looks like a pair of scissors with blunt, lockable blades that holds a hooked needle. The participant grasped the needle driver with the dominant (right) hand and placed the ancillary hand (left) in a neutral position (Figure 3).

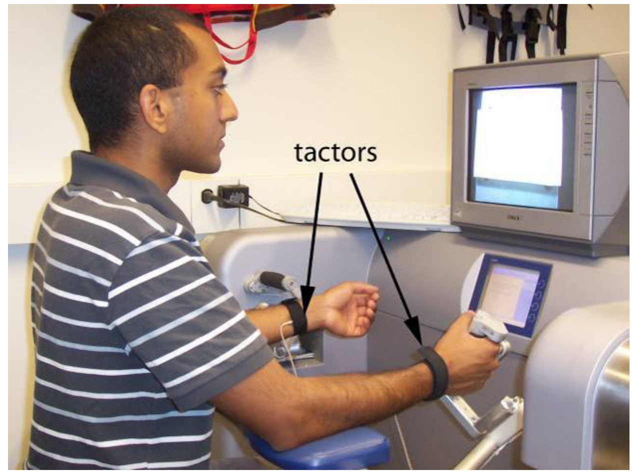

Figure 1. A participant operating the master surgical robot with his right hand. Two tactors are attached to the volar sides of his wrists via Velcros

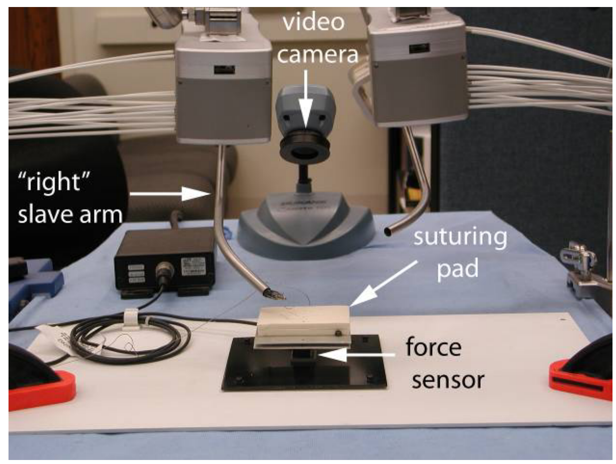

Figure 2. The slave robot setup. Shown are the video camera, the "right" arm holding a needle driver, the suturing pad and the force sensor

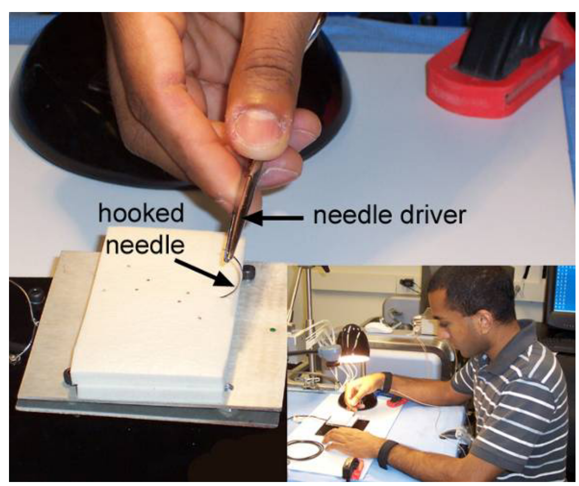

Figure 3. A participant inserting a hooked needle by hand using a needle driver instrument

To simulate human tissues, a sponge-type material (ShelfCover Antimicrobial, WEP Enterprises, Roswell, GA) was securely affixed to a base-plate with double-sided tape. The tissue assembly was screwed onto a nano-17 force/torque sensor (ATI Industrial Automation, Apex, NC) that was in turn attached to a steel plate to prevent undesired movements (Figure 4). Force and torque applied to the tissue assembly were recorded at a sampling rate of 100 Hz, which was sufficient since human motor output is bandwidth limited to 2-3 Hz [13].

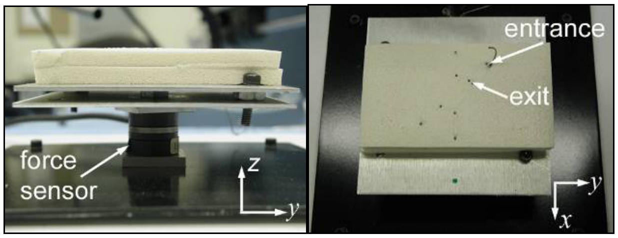

Figure 4. Close-up side (left panel) and top (right panel) views of the suturing pad and force sensor assembly. Also shown are the four pairs of entrance/exit points for the suturing task where one pair has been labeled

2.2 Participants

Four participants (1 female and 3 males, age range 22-41 years old, average age 30 years old) took part in the experiment. Participants S1-S3 had no prior experience in suturing with a curved needle or manipulating a surgical robot. Participant S4 was experienced with the task from previous work on the Laprotek robot. All are right-handed by self report. None of the participants reported any sensory or motor impairments with their hands or arms.

2.3 Task and Design

The suturing task entailed inserting a curved suturing needle through a pair of dots drawn onto the suturing pad material. The needle was always inserted into the dot near the edge of the pad and exited from the dot near the center of the pad (see Figure 4, right panel).

An "ideal" trajectory for needle insertion required the participant to drive the hooked needle through the tissue pad along a vector that originated from the outer dot (the entrance point) and extended to the inner dot (the exit point), and that the hooked needle remained in a vertical plane (perpendicular to the *x-y* plane). Any deviation from this "ideal" trajectory may cause unnecessary, extraneous tangential forces on the tissue sample and can lead to needle rotation.

Participants performed the task by hand (Hand) or with the surgical robot (Robot), with or without the vibrotactile (V) feedback of needle deviation information. For each of the four experimental conditions, four pairs of entrance/exit points (suturing directions) were tested and each pair was repeated 5 times (see dots on the suturing pad shown in Figure 4, right panel). The upper two pairs of points corresponded to a fore-hand insertion position, whereas the bottom two pairs required a backhand posture. The ordering of the four blocks of trials corresponding to the four experimental conditions was counter-balanced across the participants. A total of 80 trials (4 experimental conditions $\times$ 4 suturing directions per condition $\times$ 5 trials per direction) were collected per participant.

2.4 Vibrotactile Stimulus

Vibrotactile feedback was provided via two tactors (VBW32, Audiological Engineering Corp., Somerville, MA) driven by a custom-made tactor-driver box (Haptic Interface Research Lab, West Lafayette, IN). The vibrations were used to indicate the amount of deviation from the ideal trajectory to the participant. The stimuli were in the form of 250-Hz vibrations gated by a 10-Hz square-wave. They were delivered to the pair of tactors attached to the participant's wrists. The amount of deviation was indicated by modulating the amplitude of vibrations as follows.

The direction of the needle through the suturing pad material was determined in the *x-y* plane from the force sensor outputs F_x and F_y. The deviation angle, α, was defined as the counter-clockwise angle between the direction of the measured force vector in the *x-y* plane and the ideal direction as defined by the vector from the entrance to the exit point on the suturing pad (Figure 5). The amplitude of vibration (A) was determined by α as well as the overall force magnitude (F_{xy}) in the *x-y* plane, as follows:

$$A = (F_{xy} / 2.0) * \log((9 * \alpha / 40) + 1) .$$

The total force magnitude F_{xy} was included in the equation to suppress the noise in tactile feedback signal during initial needle insertion where the overall force magnitude was small and the needle heading varied greatly. The logarithmic function was used to amplify changes in α for smaller α values. The constants in the equation were empirically tuned to ensure a large dynamic range of vibrotactile amplitude with minimum saturation. Only one of the tactors was turned on at any given time, as determined by the following rules. If a clockwise rotation was required in order to bring the needle into alignment with the ideal direction (i.e., $\alpha \geq 0$ as shown in Figure 5), the left tactor was activated. If a counter-clockwise rotation was required, the right tactor was activated. This rule was admittedly arbitrary and seemed "natural" to only some of the participants but not others. However, it was nevertheless easy to get used to after a few trials. The participant learned to "steer" the needle towards the ideal trajectory whenever a vibration was felt at either wrists. A dead-band of $\alpha \in (-5^\circ, +5^\circ)$ was implemented so that the participants knew they were heading the right direction by the absence of vibrations on either wrist.

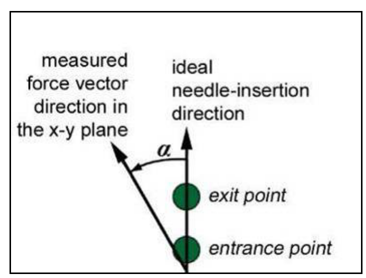

Figure 5. Top-view Illustration of the force deviation angle (α) in the *x-y* plane

2.5 Procedure

Practice trials were conducted before each experimental condition, with and without vibrotactile feedback. Participants were allowed to practice until they could comfortably complete the suturing task at each of the four suturing directions. The training time ranged from 10-30 minutes for the Hand trials to 1-4 hours for the Robot trials. During the experiment, the experimenter assisted the participant by clamping the hooked needle in the needle driver

(Hand trials) or in the jaws of the slave robot (Robot trials). On each trial, the needle-insertion direction was randomly selected and indicated on a computer screen using a diagram similar to that shown in Figure 5. A 30-second timer was activated upon initial contact[1] of the needle with the suturing pad, as measured by the force sensor. A trial was terminated by either the emergence of the needle from the suturing pad or at the end of the 30-second period. A trial was repeated if (i) the 30-second timer elapsed before the tip of the needle emerged near the exit point, (ii) the needle rotated in the jaws of the slave robot (Robot trials) or the needle driver (Hand trials), (iii) the entrance or exit point was missed by more than 10 mm (by visual inspection of the experimenter), or (iv) the hooked needle was not held in the vertical plane (a necessary condition for presenting side-loading forces on the needle).

2.6 Data Analysis

During each trial, the forces along the *x*, *y* and *z* axes as well as the value of α were recorded at a sampling rate of 100 Hz. The beginning and end of each trial, as defined by the time when the needle was inserted into the suturing pad and when it emerged from the exit point, was marked by the experimenter after the experiment. In addition to the average time for each trial, the following performance metrics were calculated: average force magnitude in the *x*-*y* plane, average force in the *z* direction, and average deviation from the ideal trajectory.

3 Results

Figure 6 shows examples of F_{xy} (top panel) and F_z (bottom panel) force traces for the experienced participant S4 with vibrotactile feedback for both Hand and Robot trials. It is immediately apparent that more forces were exerted during Hand trials than during Robot trials and that Robot trials took longer than Hand trials. A more detailed analysis is provided below.

Figure 7 shows the average force magnitudes in the *x*-*y* plane, grouped by the experimental conditions. The force magnitudes varied from 0.84 N (S3, Robot without V) to 1.91 N (S4, Hand without V). There were no discernable pattern for the participants; i.e., no one participant consistently exerted more or less forces in the *x*-*y* plane than the others across the four experimental conditions. Visual inspection failed to declare any of the four experimental conditions to have the maximum or minimum amount of force. An analysis of variance (ANOVA) performed on the *x*-*y* force magnitude with the factors Feedback (with or without V), Mode (Robot or Hand), Location (4 pairs of entrance/exit points) and Participant (S1-S4) indicated that Mode and Participant were significant factors [Mode: $F(1, 255) = 23.03$, $p < .0001$; Participant: $F(3, 255) = 16.32$, $p < .0001$], but not Location [$F(3, 255) = 1.22$, $p = 0.3027$] or Feedback [$F(1, 255) = 3.42$, $p = 0.0656$]. Subsequent Tukey tests revealed that more force was exerted in the Hand trials (mean = 1.36 N) than in the Robot trials (mean = 1.16 N), largely due to the significant drop in S4's force data.

Figure 8 shows the average force magnitudes along the *z*-axis, grouped by the experimental conditions. The force magnitudes varied between 0.21 (S2, Hand with V) and 0.93 N (S4, Hand without V). Visually, the data patterns in Figure 7 and 8 are quite similar, with a scaling factor of roughly 2 along the force axis. An ANOVA performed on the *z* force magnitude with the factors Feedback, Mode, Location and Participant indicated that all four

[1] A "contact" was detected if the force magnitude in the *x*-*y* plane, $|F_{xy}|$, exceeded 0.09 N. The threshold was tuned empirically.

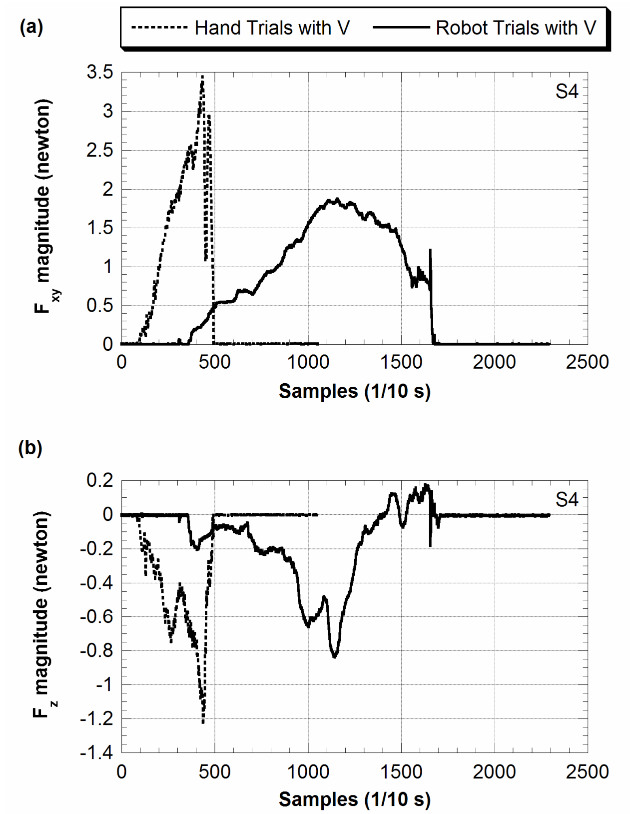

Figure 6. Example force traces for the experienced participant S4 when vibrotactile feedback was available. Panel (a) shows the F_{xy} force for Hand and Robot trials, and panel (b) the F_z forces

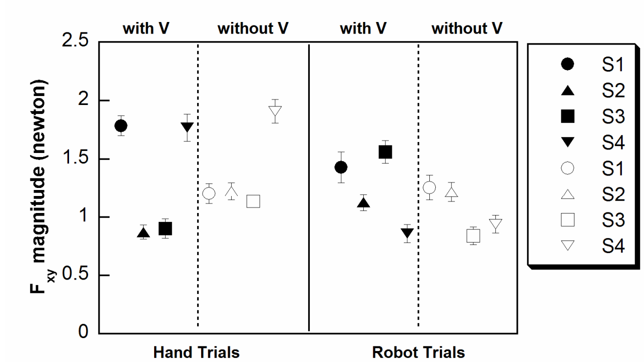

Figure 7. Average force magnitudes in the *x*-*y* plane, shown separately for the four participants for the Hand trials (left half) and Robot trials (right half). Filled symbols are the averages for trials with vibrotactile feedback and open symbols are for trials without. Error bars indicate standard errors. The data for the same condition are slightly offset from each other for clarity

factors were statistically significant [Feedback: $F(1, 255) = 6.74$, $p = 0.0099$; Mode: $F(1, 255) = 16.97$, $p < .0001$; Location: $F(3, 255) = 7.57$, $p < .0001$; Participant: $F(3, 255) = 24.31$, $p < .0001$]. Subsequent Tukey tests revealed that larger forces were exerted without vibrotactile feedback (mean = 0.56 N) than with feedback (mean = 0.49 N). In addition, larger forces were used in the Hand trials (mean = 0.58 N) than in the Robot trials (mean = 0.47 N), again mainly due to S4's force data.

Figure 9 shows the average force-direction deviations in the *x-y* plane, grouped by the experimental conditions. The α values varied from 7.5° (S4, Hand with V) to 24.7° (S2, Hand with V). An ANOVA performed on the α values with the factors Feedback, Mode, Location and Participant indicated that Feedback and Participant were significant factors [Feedback: $F(1, 255) = 16.19$, $p < .0001$; Participant: $F(3, 255) = 6.82$, $p = .0002$], but not Mode [$F(1, 255) = 0.06$, $p = 0.8058$] or Location [$F(3, 255) = 2.46$, $p = 0.0629$]. Subsequent Tukey tests revealed that force directions deviated more from the ideal directions without vibrotactile feedback (mean = 15.6°) than with the feedback (mean = 11.8°).

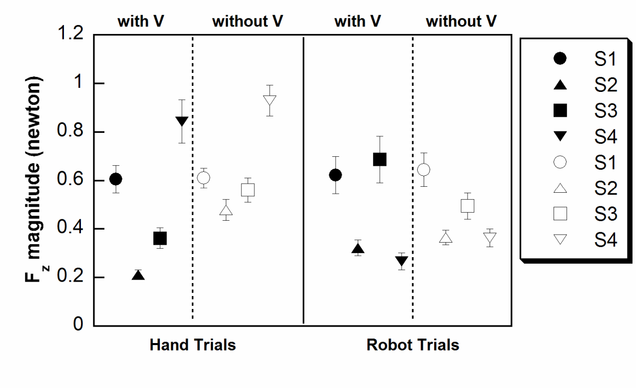

Figure 8. Average force magnitudes along the *z*-axis, shown separately for the four participants for the Hand trials (left half) and Robot trials (right half). Filled symbols are the averages for trials with vibrotactile feedback and open symbols are for trials without. Error bars indicate standard errors. The data for the same condition are slightly offset from each other for clarity

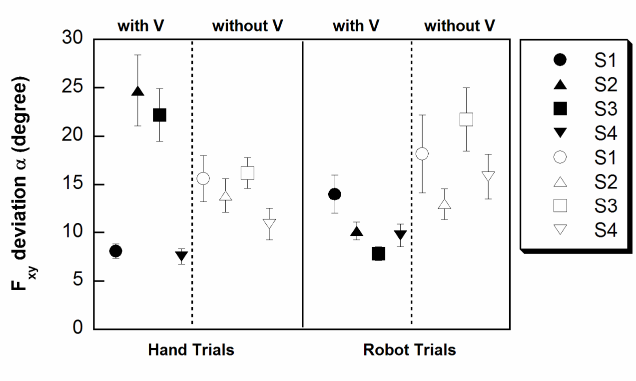

Figure 9. Average deviation in force direction in the *x-y* plane, shown separately for the four participants for the Hand trials (left half) and Robot trials (right half). Filled symbols are the averages for trials with vibrotactile feedback and open symbols are for trials without. Error bars indicate standard errors. The data for the same condition are slightly offset from each other for clarity

Finally, Figure 10 shows the duration of each trial averaged across the four participants. It is apparent that the Robot trials took about twice as long as the Hand trials, and the trials with vibrotactile feedback took longer than the trials without it (by 1.51 and 1.46 s in Hand and Robot trials, respectively).

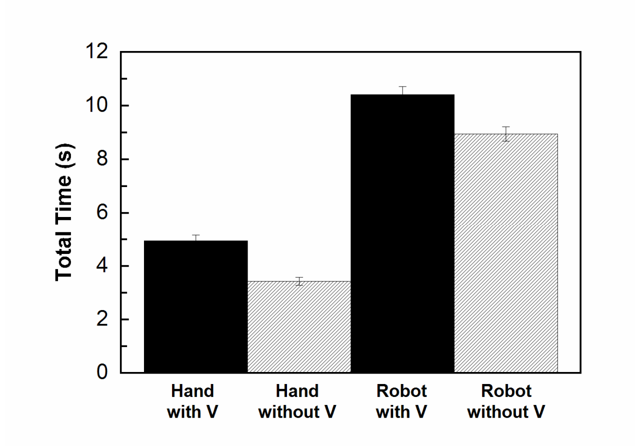

Figure 10. Total time per trial, averaged across the participants. Also shown are the standard errors

4 Summary and Discussion

This study examined the effect of vibrotactile feedback in reducing deviations in needle-insertion direction in a surgical suturing task. Our results showed that vibrotactile feedback had a significant effect at reducing the *x-y* force deviations. Furthermore, the vibrotactile feedback resulted in a smaller force magnitude along the *z* axis but had little effect on the force magnitude in the *x-y* plane. It was also found that, mainly for the experience participant S4, larger forces were exerted during the Hand trials than during the Robot trials, for both *x-y* and *z*-direction forces. Finally, the Robot trials lasted longer than the Hand trials, and the vibrotactile feedback increased the trial duration by about 1.5 seconds.

Our finding that the vibrotactile feedback resulted in a small *z*-force was consistent with other studies (e.g., [4]). However, it was puzzling that the vibrotactile feedback had an effect on *z*-force but not the *x-y* force magnitude, since it incorporated the magnitude of F_{xy} but not F_z. The finding that larger forces were exerted in the Hand trials than in the Robot trials may be mainly due to S4's dexterity with the surgical robot. The result that vibrotactile feedback increased task execution time is also consistent with the findings from other studies employing haptic feedback (e.g., [7, 14, 15]).

Numerous studies have investigated the assessment of surgical tasks and the effect of various feedback mechanisms in surgical training (e.g., [16-19]), but many challenges remain. A recent review of surgical simulation system concluded that despite many compelling reasons to reduce surgical training on patients and animals, none of the methods of simulated training (from low-tech mockups to high-tech computer simulation) has been shown to be better than existing methods [20] (although see [21, 22]). The review also pointed out that few methods have gone through a comprehensive and rigorous testing in terms of construct validity, instructional effectiveness, predictive validity, reliability, and ultimately, influence on patient care outcomes. We are aware of one recent project, the Haptic Cow, that has demonstrated unequivocally the benefit of haptics-enabled virtual reality training for veterinary students [22]. But as another review of haptics in education pointed out, there is still little evidence for a positive cognitive impact of haptic technology on student learning [23]. Our own experience from the present study has revealed many reasons why conducting empirical assessments of skill training is a difficult endeavor.

First, we found that gaining dexterity with a surgical robot was mentally and physically challenging and required a level of commitment beyond that could be expected from an average participant recruited through an advertisement. It took several hours of training before some of the participants in the present study felt comfortable operating the surgical robot. This was consistent with the 6-8 hours training time reported in [24] for gaining baseline proficiency at operating a surgical robot. Although the use of a monoscopic camera view might have contributed to some of the difficulties, most of the frustrations experienced by the participants could be attributed to the characteristics of the surgical robot used in the present study. It remains to be seen whether participant training could be improved with a more advanced surgical robot. Second, by using a relatively lower-cost method of vibrotactile feedback, somewhat arbitrary decisions on parameter selections (body site stimulated, binary vs. varying-intensity signal, scaling factor, mapping between direction of deviation and body site stimulated, etc.) had to be made to map force deviation information to vibrotactile signals. Despite every effort of the researchers, it would still be difficult to argue that the "optimal" encoding scheme had been used in the present study. It would simply be too time consuming to fine-tune these parameters. It was also unclear to what extent the participants should have been trained longer with the vibrotactile signals. Third, the hooked needles became dull after repeated insertion into the simulated tissue pad. This was dealt with by replacing the needles at a fixed number of trials, assuming that dulling occurred at a constant rate. This introduced yet another uncontrolled variability in our experimental setup. The use of suturing pads in the future may alleviate this problem. Finally, the visual feedback was limited by the resolution of the camera-monitor setup. We also found that moving the light source and the camera angle had a dramatic effect on the Robot trials in terms of highlights on needles, occasional occlusion, and the interpretation of certain slave robot end-effector configurations.

In the future, we will refine the experimental design along the lines discussed above, and repeat the experiment on a higher-performance surgical robot, such as the daVinci system (Intuitive Surgical, Sunnyvale, CA). We are interested in finding out if participant training can be easier with the daVinci system and whether the increase in task completion time can be minimized or eliminated by more extensive training with the vibrotactile feedback signals. Ultimately, we need to improve the clinical relevance of the experimental setup and employ surgeons and surgical residents as participants to gauge the applicability of using vibrotactile feedback for improving needle-insertion performance in a suturing task.

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