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Robotic Suturing Forces in the Presence of Haptic Feedback and Sensory Substitution

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Abstract – **There has been some interest in recent years on how information about interactions happening between surgical instruments and tissue during robot-assisted surgery could improve the efficiency and reliability of a surgical task. In this paper, it is hypothesized that various modes of sensory feedback have the potential to enhance performance in robot-assisted surgery in terms of the amount of applied forces. User performance during telemanipulated suturing is compared for cases where force feedback is replaced or complemented by visual representation of the force levels. In addition to confirming the above hypothesis, the results indicate a trade-off between the magnitudes of applied forces and the time required to complete the task.**

I. Introduction

With endoscopic surgery (also called minimally invasive surgery), an endoscope and endoscopic instruments are inserted into the body cavity through small incisions. Due to the small incision size, the trauma to the body, the post-operative pain and the length of hospital stay are reduced significantly compared to open surgery. However, there are inherent drawbacks that hinder the conduct of endoscopic operations. These drawbacks include limited dexterity for the surgeon, magnification of hand tremors by the long instruments, awkward hand-eye coordination, and lack of haptic feedback about instrument/tissue interactions to the surgeon.

The limitations demonstrated by endoscopic surgery can be tackled by means of robots, which have found extensive use in assisting surgical interventions [1-4]. The currently available robotic surgical systems (the da Vinci and the Zeus systems from Intuitive Surgical Inc.) are equipped with end-effectors that articulate near the end to increase dexterity and manipulability, allow precise movements through scaling hand motions, and filter out hand tremors. Moreover, these robots provide three-dimensional vision and enhance eye-hand-instrument alignment.

As far as restoring force feedback to the surgeon is concerned, however, the available robotic systems have not yet been successful. While the surgeon's console of the da Vinci system has force feedback capability in some of the available degrees of freedom, this feedback is of low quality, and therefore disabled by the manufacturer. The main reason for this is that the interactions between the da Vinci's end-effector and the environment are estimated from outside the patient instead of being directly measured. This leads to inaccuracies since estimation of tool/tissue interaction from outside the patient is plagued by disturbances, bias and noise caused by the entry port†. Study of robot-assisted suturing has also shown that estimation of tip interactions from joint torques is of little value [6]. As a result of the above, it is clear that providing full-state haptic feedback in a complex system such as the da Vinci is a long-term effort involving several technical challenges.

The lack of haptic feedback capability in the current generation of surgical robotic systems is a major problem especially when working on delicate tissue where exerting large forces can be detrimental. The implications of lack of haptic feedback during robot-assisted soft-tissue interventions include possible complications such as accidental puncturing of blood vessels or tissue damage as the surgeon has to rely on visual cues [7, 8], and endangering the surrounding organs if the instruments are outside the field of view. On the other hand, during robot-assisted surgery, the presence of haptic feedback can facilitate the optimal application of forces by relaying the required perceptual information to the surgeon. Haptic feedback can also enhance the precision of the procedure and increase its speed by eliminating the need for awaiting visual cues as to the strength of the grip, the softness of the tissue, etc. [9].

As a solution to the problems caused by lack of haptic feedback, this paper hypothesizes that various modes of sensory feedback have the potential to enhance performance in robot-assisted surgery in terms of the amount of applied forces and the resulting trauma to tissue. As such, Section II of the paper discusses an alternative mode of presenting haptic information to the user. The rest

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† A recent study explores a solution in which the force/torque sensor is integrated into the trocar and stays outside the patient without picking up the friction at the trocar [5].

of the paper is organized as follows: Section III describes a force-reflective master-slave system for an endoscopic surgery environment, which is used as the test-bed for conducting experiments. Section IV explains the experimental procedures and the tests that were conducted to determine performance improvements during telemanipulated suturing for different modalities of haptic feedback. Section V contains the results and Section VI includes some discussion and concluding remarks.

II. Sensory Substitution for Haptic Feedback

Sensory substitution for haptic feedback is the act of replacing kinesthetic haptic feedback to the surgeon by other sensory cues such as visual representation of haptic information. For instance, a bar indicator whose height varies with the magnitude of gripping forces has been added to a version of the Zeus system, thus providing visual feedback of tool/tissue interactions to the user. Nevertheless, there is more than one way of replacing haptic feedback, e.g., by auditory, visual, and vibro-tactile feedback. The ideal channel for sensory substitution should be intuitive and provide a straightforward mapping to haptic information. It should have minimum background noise, and have a fairly large bandwidth. In an operating room, the conversations within the surgical team can interfere with auditory signals corresponding to haptic information and surgeons may not in general be familiar to vibro-tactile inputs. However, visual display of haptic information overlaid on or beside the view of the surgical site (Figure 1) can be useful as the surgeon's side view should be able to receive enough haptic data based on the size and color of the visual stimuli. While force feedback remains a more intuitive means of relaying haptic information to the user, visual sensory substitution for force feedback (or "visual force feedback") may be able to provide sufficient feedback of an instrument's contact with tissue under certain conditions.

Study of the effect of sensory substitution for a peg-in-hole insertion task has shown that both visual feedback and vibro-tactile feedback of haptic information can reduce the peak forces compared to the case where no feedback of haptic information is provided to the users [10]. For the suturing task, quantifying the difference in the user's performance between manual operation and robotic teleoperation in presence of auditory/visual sensory substitution has been the subject of another study [11]. Nevertheless, it remains to be seen what the difference in terms of performance is between sensory substitution and actual haptic feedback during robotic teleoperation. As such, in this paper we compare the suturing performance in terms of the magnitudes of applied forces for the case that haptic feedback is provided to the user's hand and the case that haptic feedback is substituted or augmented by corresponding visual information.

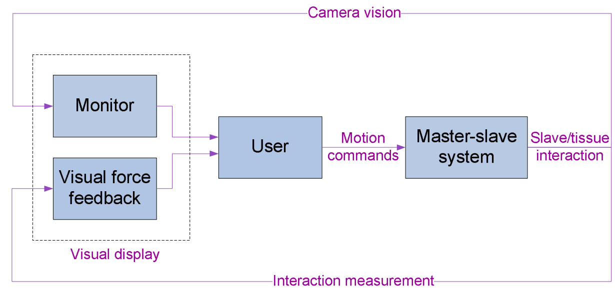


Figure 1: Sensory substitution for haptic feedback.

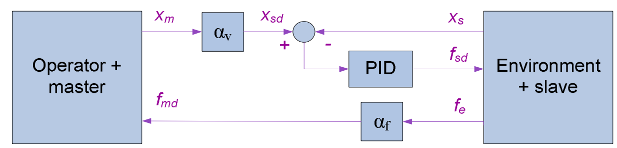


Figure 2: Bilateral control through direct force reflection.

III. System Description

A master-slave system appropriate for use in an endoscopic surgery environment has been developed. Through the master interface, a user controls the motion of the slave arm (surgical tool) and receives force/torque feedback of the slave-environment interactions. Using direct force reflection as the bilateral control scheme, the slave is controlled using a PID compensator such that it follows the measured position of the master, while the master is controlled such that it exerts a force (or torque) to the user equal to the measured interaction at the slave (Figure 2). The bilateral control law can be written as:

$$\tau_s = k_P(\theta_m - \theta_s) + k_D(\dot{\theta}_m - \dot{\theta}_s) + k_I \int(\theta_m - \theta_s)dt$$

$$\tau_m = \alpha_f \tau_e$$

where θ_m, θ_s, τ_e, τ_m and τ_s are the master position, the slave position, the interaction between the slave and the environment, the control signal for the master and the control signal for the slave, respectively. The control parameters are $\alpha_v = \alpha_f = 1$, $k_P = 24$, $k_D = 8$ and $k_I = 0.2$. The slave and master subsystems are briefly described next.

A. Sensorized surgical tool

The slave's surgical tool (Figure 3a) is an endoscopic instrument that can serve as the end-effector of a surgical robot. The instrument actuates the open/close motions of a tip and rotates about its main axis using the geared motor/encoder combination placed at the base of the end effector. The instrument is properly sensorized to measure its interactions with tissue in the form of forces or torques in all five degrees of freedom present in endoscopic operations (pitch, yaw, roll, insertion and tip open/close). Due to the problems posed by the incision size constraint in minimally invasive surgery, strain gauge sensors are integrated into the end effector to provide a non-invasive, efficient way of measuring interactions with tissue; Figure 3b shows the gauge used for measuring twist moments applied to the tip during suturing. For more details about this sensorized surgical tool, see [12].

B. *Force-reflective user interface*

The haptic user interface acting as the master is shown in Figure 4a. This haptic feedback device is capable of providing the user with force sensation, sensation regarding surface roughness, and kinesthetic sensation of the elasticity of an object. A PHANToM 1.5A, which provides haptic feedback in three translational DOFs, is integrated into the user interface. A rigid shaft similar to an endoscopic instrument is passed through a fulcrum and attached to the PHANToM's endpoint, causing the motions of the handles grasped by the surgeon to be similar to those in endoscopic manipulation. Since the pitch, yaw and insertion motions of the instrument span the 3D Cartesian workspace of the PHANToM, force reflection is provided by the PHANToM in these three directions in the endoscopic instrument workspace. In addition, mechanisms for force reflection in the roll and gripping directions are incorporated into the interface. As shown in Figure 4b, a single-DOF haptic mechanism is used to establish force reflection in the twist direction (i.e. rotations about the instrument axis).

IV. Experiment Design

The master and slave subsystems, tailored for establishing force-reflective teleoperation in the twist direction only (i.e. rotations about the instrument axis) as needed for suturing are shown in Figure 5. In this setup, sixteen light-emitting diodes, which form a bar indicator for visual force feedback, are located beside the screen that shows the tissue site to the user. As shown in Figure 5, the user manipulates the master haptic interface to drive an arced suturing needle (Ethicon PG-J346 size 0 and PG-J353 size 0) attached to the slave instrument for piercing the tissue. In manual operation, driving a suturing needle involves one rotation and one translation; the surgeon has to bring his/her hand close to the surface being sutured while rotating the needle so that the needle can travel a circular trajectory without causing excessive damage to tissue (Figure 6). In robotic operation, however, for simplicity and to limit the required motions to a single rotation about the instrument axis, we bent a short portion of the needle near the blunt end and just in front of where it is held by the slave instrument, such that the needle moves in a circular arc as the instrument rotates about its axis (Figure 6).

Eight subjects (4 males, 4 females) aged 24-34 participated in the suturing experiments. Subjects had little to average exposure to haptic feedback, little exposure to visual sensory substitution, and no experience with suturing. Each test consisted of 10 trials (i.e., 10 suturing operations of the needle). In each trial of each test, the

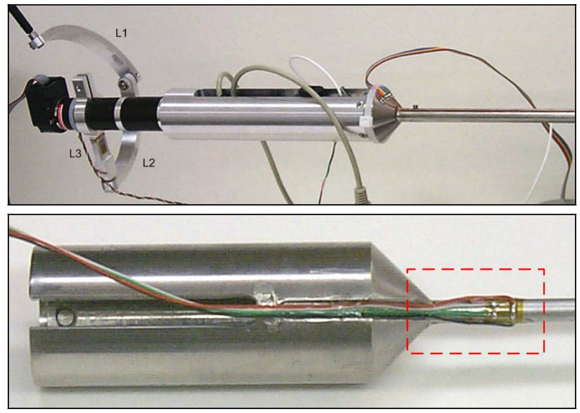
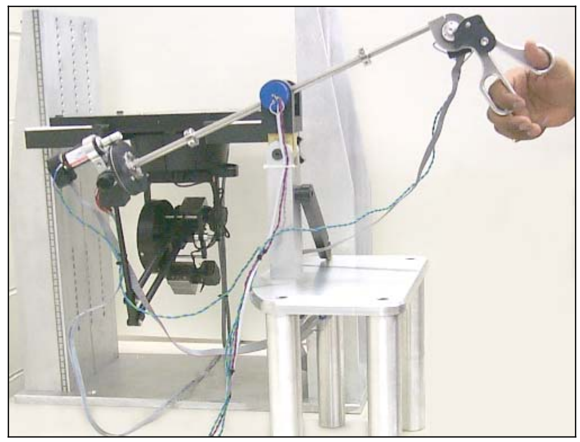


Figure 3: From top to bottom: (a) the slave's end-effector, (b) the gauge used to measure the torsional moment.



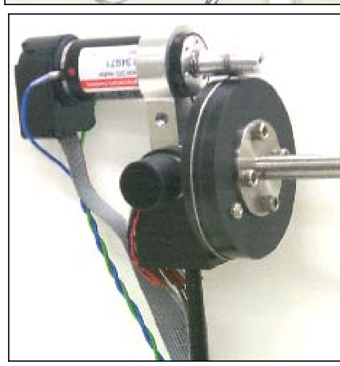


Figure 4: From top to bottom: (a) the master interface, (b) the single-DOF mechanism for force reflection in the twist direction.

contact forces between the instrument and the tissue were recorded for subsequent analysis. Four different tests were conducted in which, in addition to the camera vision, subjects received various forms of sensory feedback about the interaction between the instrument and the tissue.

- Test 1: The subjects did not receive any feedback of the contact between the instrument and the tissue other than camera vision.
- Test 2: The subjects received visual feedback about the level of interaction between the instrument and the tissue in addition to the camera vision.
- Test 3: The subjects received haptic feedback of the interaction between the instrument and the tissue in addition to the camera vision.

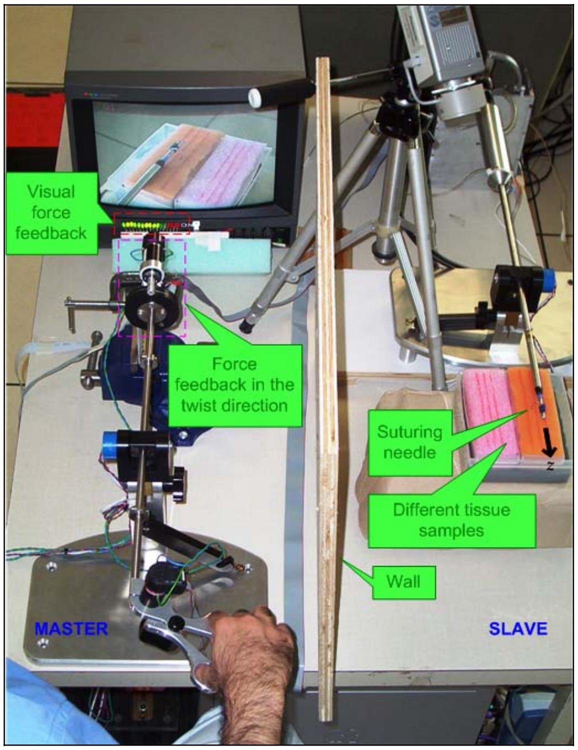


Figure 5: The master-slave setup for performing telemanipulated suturing tests.

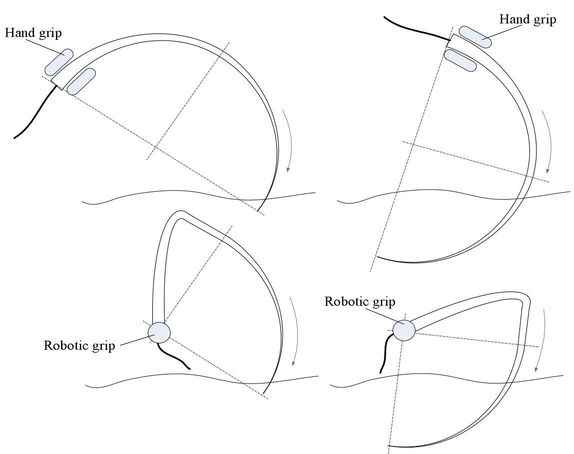


Figure 6: Circular trajectory of the needle during manual (top) and robotic (bottom) suturing. Sequence of events is from left to right.

- Test 4: The subjects received both visual and haptic feedback of the interaction between the instrument and the tissue in addition to the camera vision.

The order of Tests 2 to 4 was randomized. Prior to the experiments, each user was given the basic information that our goal was to compare the user performance under visual force feedback (VFF), kinesthetic force feedback (FF) and both visual and kinesthetic force feedback (VFF+FF) in terms of the magnitude of instrument-tissue interaction forces (as the needle is pushed in during each suturing operation). With regard to the time to complete each test, two different sets of the above four tests were done. In the first set of tests, which we call free-time tests, the users were told that the task completion time is a secondary performance metric that needs to be minimized, yet they could take their time if it helps to minimize the primary performance metric (i.e., level of forces). In the second set of tests, which we call fixed-time tests, the users were restricted using two periodic auditory signals to start and complete each suturing motion within fixed time intervals.

Four different tissue samples were used in the tests. The first three samples, which were made of foam material but with stiffness increasing from material #1 to material #3, were used in the free-time tests. The fourth sample, which was a sample tissue model (from the Chamberlain Group, LLC.) with the highest stiffness among all, was used in the fixed-time tests. Through trials, 12 seconds was determined to be the average time required by a user to complete one suturing motion on the tissue sample used in fixed-time tests (sample #4). This is consistent with the timeline for suturing in conventional endoscopic surgery [13]. The users were given 5 additional seconds to retract the needle and get ready for the next move. Each suturing motion involved orienting the needle such that is came in contact with the tissue followed by biting the tissue until the tip of the needle emerged on the other side (equal to a wrist rotation of 180° for the user).

V. RESULTS

In the graphs in this section, τ_z (in N.m.) is the torque about the slave instrument axis due to the instrument-tissue interaction, which is measured by the gauge shown in Figure 3b. Positive values for torques correspond to when the needle is being pushed into the tissue, while negative values are the result of needle retractions.

(1) Based on tests 1 to 3 (both free-time and fixed-time), it was found that when no visual or haptic feedback about slave-tissue interactions (other than camera vision) was provided to the users, they applied quite large amounts of force to the tissue (e.g. subject #3 with material #3 as shown in Figure 7). Also in the free-time tests, the task completion times were the shortest with no feedback compared to the cases where visual or haptic information is provided to the user.

(2) Comparing the results of free-time tests 2 and 3, it was found that VFF can potentially reduce contact forces compared to FF (e.g., subject #7 with material #1 as shown in Figure 8). In fact, the forces exerted on the tissue were lower with VFF in cases where the users paid enough attention to the sensory cues provided in the form of visual representation of force levels. In such cases, the reduction in force levels came at the expense of longer task completion times as the users had to constantly refer to the visual display to see and limit the forces. However, in other cases where the time to perform the task under VFF was shorter than for FF, the applied forces turned out to be higher with VFF than FF (performance-speed tradeoff).

(3) A variation of test 2 (both free-time and fixed-time) was used to compare the user performance when the full-

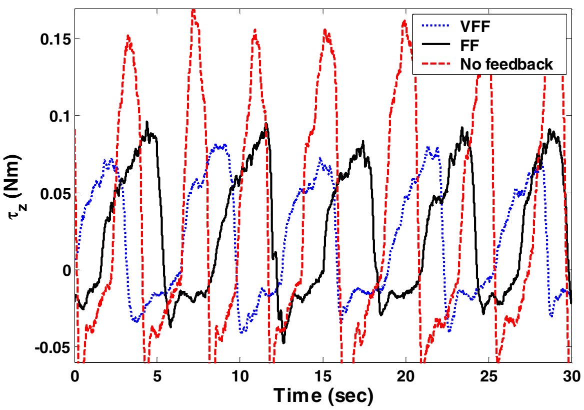


Figure 7: Measured torques with no feedback (dashed), with VFF (dotted), and with FF (solid).

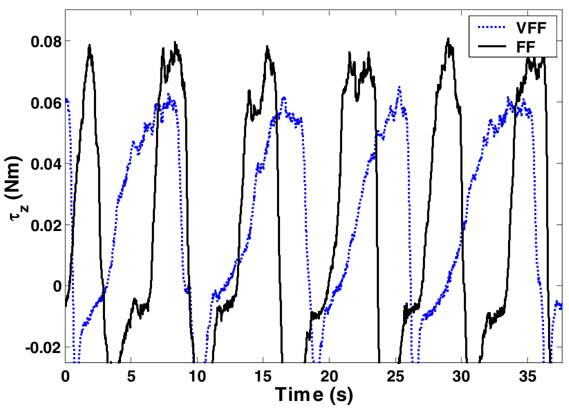


Figure 8: Measured torques with VFF (dotted), and with FF (solid).

scale length of the visual bar was reduced by half. As Figure 9 shows for subject #5 and material #4 (fixed-time test), scaling down the visual bar results in application of larger forces.

(4) Comparing the results of free-time tests 3 and 4, it was determined that supplying both VFF and FF at the same time (VFF+FF) could be better than providing FF alone. With VFF+FF, it normally took users longer than FF to complete the task, but in return the exerted forces were smaller (e.g. subject #3 with material #3 as shown in Figure 10). In some cases, VFF+FF even helped the users to apply forces more consistently after the tissue had been punctured, but at the expense of time.

VI. Discussion and Concluding Remarks

Result 1 shows that when a user does not receive any feedback about the interactions happening between the tool and tissue, he/she may apply excessive forces on the tissue, thus increasing the risk of damage to the tissue. While providing visual or haptic feedback about tool/tissue interactions is shown to be effective in reducing the forces, the corresponding task times are longer because more information requires more cognitive processing by the users.

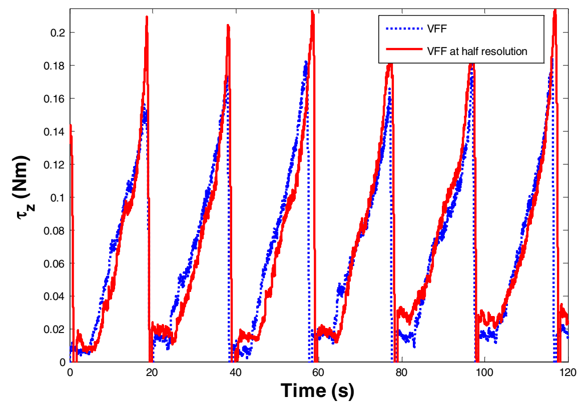


Figure 9: Measured torques under VFF (dotted) and VFF with reduced sensitivity (solid).

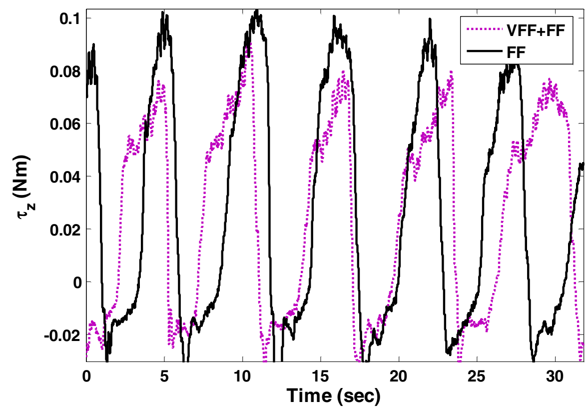


Figure 10: Measured torques with VFF+FF (dotted), and with FF (solid).

One reason for the superior performance achieved with VFF compared to FF (Result 2) is that the sensitivity of a visual force indicator is only limited by the resolution of the force measurements while the sensitivity of the human hand for force sensing is limited in nature (0.5 N or 7 % is the just-noticeable difference [14]).

Result 2 also highlights the performance-speed tradeoffs (i.e., contact forces versus task times) for VFF. Consistent with previous results for teleoperation of non-surgical tasks [15], visual display of forces results in longer task completion times. The experiments leading to Result 2 also demonstrate that constant visual attention to a visual indicator followed by cognitive processing could cause fatigue. Once the user became tired and therefore did not pay enough attention to the presented visual information, he/she would compromise the magnitude of applied forces for the time to complete the task. The need for human processing and interpretation may be a major drawback to VFF especially for dexterous tasks, in which the user has to keep track of several visual indicators and switch his/her attention between them without getting distracted from the main surgical task.

With VFF, a user will perform well only if the sensitivity of the visual display to force variations is high so that small changes in forces can be seen. Otherwise, as shown by

Result 3, the users will have less control over the magnitude of exerted forces.

Result 4 demonstrates that force feedback accompanied by sensory substitution is effective in relaying more task information to the user concerning tool/tissue interactions. Again, as more information is provided to the users, longer task times are needed to understand and act on the information.

The task considered in these experiments consisted of a 1-DOF rotation about the instrument axis. For dexterous tasks, however, VFF can be difficult to handle if the user is to keep track of several displays during teleoperation. Based on the results of this paper, VFF can provide sufficient feedback of an instrument's contact with tissue (and outperform FF in terms of exerting lower forces on the tissue under equal conditions) for a 1-DOF task on soft tissue and for a short period of time.

To summarize, in this paper performance comparisons have been made for the situations in which haptic feedback is replaced or augmented by visual feedback. It was found that complementing force feedback by a visual representation of the force levels could potentially assist the user in exerting lower amount of forces on tissue during telemanipulated suturing maneuvers, thus reducing the trauma and the risk of damage to the tissue. Moreover, in cases where a haptic master interface is not available, visual force feedback can be substituted for actual force feedback provided that small variations in the force are clearly shown on the display.

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