Short Papers

Force Feedback Benefit Depends on Experience in Multiple Degree of Freedom Robotic Surgery Task

Christopher R. Wagner and Robert D. Howe

***Abstract*—Force feedback has been suggested to provide a number of benefits to surgery. Few studies, however, have addressed the benefit of force feedback in the context of the complexities of true surgical tasks. When information is limited (such as depth information in endoscopically guided tasks), force feedback may provide additional information that improves performance. We investigate a two-handed, six degree of freedom, endoscopically guided, minimally invasive cannulation task (inserting one tube into another tube) to test this hypothesis. We used twelve subjects, six of whom were experienced minimally invasive surgeons. Results suggest that force feedback reduces applied forces for both subject groups, but only the surgically trained group can take advantage of this benefit without a significant increase in trial time. We hypothesize that this training difference is due to the interaction between visual–spatial motor abilities and the information contained in the mechanical interaction forces.**

***Index Terms*—Force feedback, haptics, robotic surgery, surgery, teleoperation.**

I. INTRODUCTION

Surgery requires executing complex motions in a 3-D environment. Many tasks, including suturing, dissection, and anastamosis require precise positioning and orientation along a path to lead to a successful outcome [1]. A primary challenge surgeons face with minimally invasive, endoscopically guided procedures is that the visual feedback is two-dimensional, while the task environment is 3-D [2]. Through training, surgeons can use other depth cues to carry out tasks in three dimensions [3]. However, interpreting 3-D space with such limited sensory information may tax cognitive abilities [4], [5]. Consequently, we hypothesize that additional information in the form of force feedback would aid performance in minimally invasive tasks.

Previous studies of force feedback in surgery have focused on tasks with limited degrees of freedom. For example, previous work on force feedback in blunt dissection investigated a single-handed, three-axis positioning task that required no changes in orientation [6], [7]. Kazi's work investigated force feedback in a number of tasks including cannulation and palpation, also using a one-handed, three-axis positioning system [8]. Other investigations involving reduced degree of freedom tasks include suturing [9] and palpation [10]. In most actual surgical tasks, surgeons must simultaneously control the positions and orientations of manipulators in both hands. Preliminary work in multidegree of freedom robotic surgery has suggested that force feedback may be useful in complex motion tasks such as knot tying [11], [12]. Consequently, a full analysis of force feedback in minimally invasive surgery must be carried out under conditions that more closely replicate the true complexity of surgical tasks.

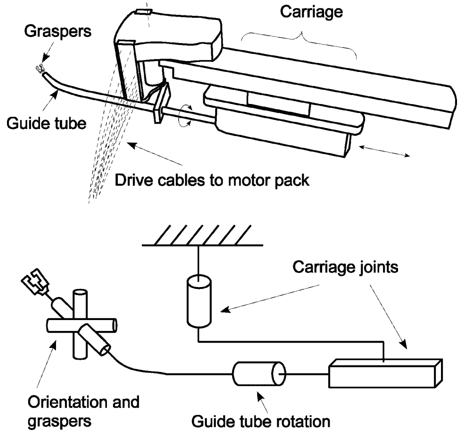

Fig. 1. Laprotek robot arm and associated kinematic representation. Note that a rotation of the guide tube results in a vertical translation of the graspers.

Here we investigate a two-handed, six degree of freedom, endoscopically guided, minimally invasive cannulation task (inserting one tube into another tube) that realistically replicates much of the complexity of a surgical task. We investigate performance on the cannulation task with and without 3-D force feedback. Our hypothesis is that the addition of force feedback will enhance performance by reducing the applied forces and the time required to complete the task because the subjects gain additional information on position and orientation. We also investigate whether the performance benefit of force feedback depends on the training of the subjects, using subjects with and without minimally invasive surgical experience.

II. METHODS AND MATERIALS

A. Teleoperation System

We used the Laprotek surgical robot (Endovia Medical, Norwood, MA) as the basis for our teleoperation system [13]. The robot provides two articulated, seven degree of freedom manipulators (three positions, three orientations, one grasping) (Fig. 1). The cable-driven, disposable surgical instrument provides two orientation degrees of freedom in the wrist articulating the surgical graspers. The instrument passes through a guide tube to access the surgical environment. Rotation of the instrument along its long axis within the guide tube provides the final orientation degree of freedom. Two joints position a carriage holding the guide tube assembly. A bend in the guide tube transforms the rotation of the tube into translational motion, providing the final translational degree of freedom. All joints are cable driven, with the motors located in a motor pack mounted to the surgical table.

Several augmentations were made to the system to allow high fidelity bilateral force feedback. To improve the stiffness of the robot at the instrument tip, we bolted the carriage directly to a rigid mechanical base. We reinforced each guide tube by passing it through a rigidly mounted spherical joint, which decreased the lever arm between the instrument tip and the mechanical base. Finally, the internal cables of the surgical instruments were retensioned to further increase instrument stiffness at the tip.

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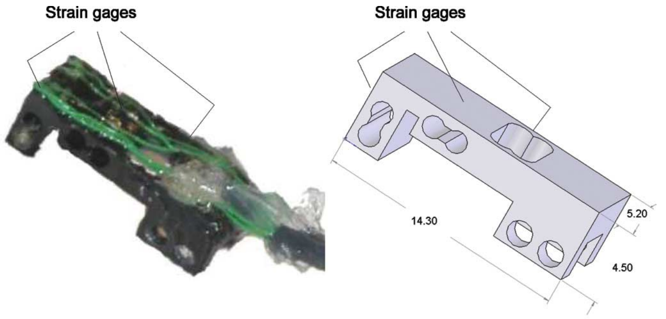
(a) (b)

Fig. 2. (a) Handle addition to Phantom haptic interface. (b) Force sensors attached to Laprotek graspers. Larger compliant tube is shown in the left hand, smaller tube in the right.



(a) (b)

Fig. 3. (a) Closeup of three-axis strain gage force sensor. (b) Diagram of force sensor showing serial chain of flexure elements and locations of strain gage pairs. Dimensions are in mm.

The Laprotek system was further augmented by replacing the standard surgeon interface with high fidelity haptic interfaces (Model 1.5, SensAble Technologies, Inc., Woburn, MA). While the original Laprotek system interface does provide some force feedback based on motor torques, the resulting feedback is only sufficient for implementing low bandwidth workspace boundary limits. The Phantom haptic interfaces allowed higher force feedback bandwidth, without torque or grasping force feedback. We added a lightweight handle (Fig. 2(a)) to the standard Phantom stylus interface to command the grasper angles. A low friction potentiometer (CP-UTX, Midori America Corp., Fullerton, CA) acted as both the axle for the finger joint and an angle sensor.

We attached a custom built, three-axis, 14 mm long force sensor to each of the grasper jaws (Fig. 2(b)). The force sensors provided interaction forces in three dimensions with an accuracy of 0.07 N and 0.1 N rms noise at 1000 Hz bandwidth. We used strain gages epoxied to a metal element to provide a high bandwidth, high resolution force sensor. The metal element consisted of a serial chain of flexures, designed for low sensitivity to moments (Fig. 3). We used a 6×3 calibration matrix as a linear mapping from strain gage voltages to applied force at the tip.

Each force sensor was machined from a single block of aluminum. After machining, the aluminum was anodized to prevent conduction through the strain gages and any stray wire contact. Anodizing the aluminum improved the strain gage sensitivity by removing the need for an insulating layer of epoxy between the base and gage. Each gage (SS-037-022-500P, Micron Instruments, Simi Valley, CA, USA) was bonded and soldered by hand under a microscope due to its small size (1 mm $\times$ 0.25 mm). The gages and wires were coated with silicon rubber to seal gages and provide strain relief.

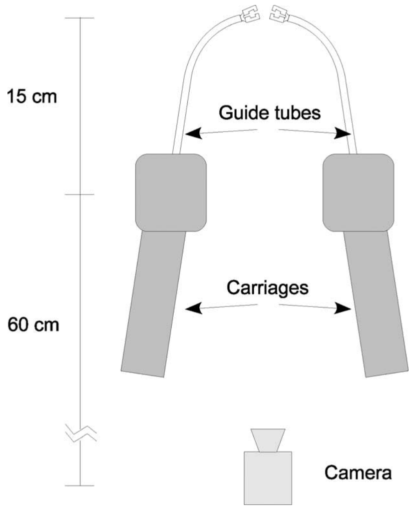


Fig. 4. Top down layout of Laprotek arms and camera. During the task, the major axis of the task tubes would be aligned perpendicular to the page.

The majority of the teleoperation system, including the haptic interface and the force sensors, was controlled by a 2.0 GHz Athlon computer running Windows XP. The teleoperation control software, written in C++ (Microsoft Visual C++ 6.0), updated the haptic interface at 1000 Hz. We used the original Laprotek system software to control the surgical robot, modified to accept position commands over ethernet. The control software uses a standard position feedforward, force feedback control scheme [14], and runs on the integrated QNX-based system, with an update rate of 95 Hz. As is standard with the Laprotek surgical robot, the position of the surgeon interfaces were mapped directly to the position of the gripper. We used position and orientation gains of 3 and 1.3, respectively, to provide the subjects with a comfortable range of motion during the experiment. These were also the default gain settings for the Laprotek system.

When force feedback was enabled, the Phantom control computer sampled the instrument forces at 1 kHz and transformed the forces to the haptic interface. A force feedback gain of 1 was used to provide high forces while maintaining system stability.

Teleoperation performance was limited by mechanical hysteresis. While position and orientation resolution was good (mean <0.5 mm in position, 3° angle resolution), instruments suffered from a tradeoff between stiffness at the wrist and hysteresis. Increasing the instrument cable tension, and the corresponding stiffness at the tip, also increased frictional forces and the resulting backlash. The magnitude of backlash depended on the joint, typically requiring a 10 mm user motion and 10° orientation change to reverse direction.

B. *Visual Feedback*

A video camera proximal to the robot arms provided visual feedback (Fig. 4). The relative orientation between the user and the monitor is approximately the same as the orientation between the camera and the graspers, to minimize the mental effort of relating visual and instrument frames [15]. However, degraded depth perception remained a source of difficulty.

C. *Cannula Insertion Model*

Two sections of tubing were used as the cannula model. One tube was a 4 cm section of stiff PVC tubing with an outer diameter of

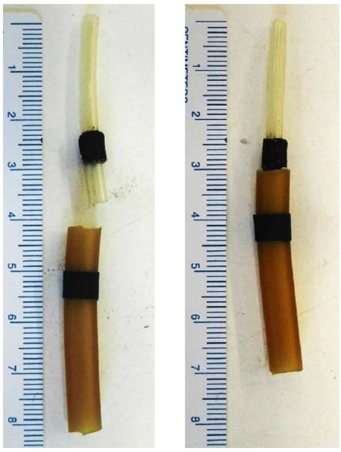


Fig. 5. Tubes unmated and mated. Larger compliant tube is the lower of the two. Grip tape bands are used to increase friction between the tubes and the grasper jaws, as well as provide a mechanical stop.

3.2 mm and a measured Young's modulus of 0.87 GPa. The other tube was a 4 cm section of compliant rubber surgical tubing with an inner diameter of 3.2 mm, outer diameter of 6.4 mm, and modulus of 3.0 MPa. The diameters and materials were chosen so that little force ($<$0.5 N) was required to insert one into the other when the two tubes were axially aligned. High friction grip tape placed around the shaft of the smaller PVC tubing limited the insertion depth to 6 mm. The difference in compliance between the two tubes provided a realistic representation of the salient mechanical interactions in a minimally invasive cannulation task. Examples of procedures involving such a task include intraoperative cholangiography [16], [17] and laparoscopic stented choledochorrhaphy [18].

D. Protocol

Subjects carried out the cannula insertion task in the presence or absence of force feedback. Subjects were asked to carry out the task as quickly and as gently as possible. No explicit tradeoff between speed and force was advised. Subjects began the task with the tips of the tubes within 1 cm of one another and with both tubes aligned vertically in the visual view (Fig. 5). Each trial was started with the compliant tube grasped with the left grasper and the smaller PVC grasped with the right. No opening or closing of either of the graspers was required during a trial.

Subjects trained for approximately 10 min to familiarize themselves with the teleoperation system and to gain a sense of the force necessary to successfully complete the task. By the end of training, all subjects could successfully join the tubes within 60 s with and without force feedback.

Twelve subjects participated in the experiment. Six subjects were surgeons, all with backgrounds in minimally invasive surgery (more than 3 years of training). We specifically chose surgeons with minimally invasive surgical training because they have experience with two-dimensional visual feedback [3] which creates a disparity between apparent visual motion and proprioceptive hand motion [19]. Six graduate students with no minimally invasive surgical experience provided an untrained population for comparison. Each subject performed ten trials with and ten without force feedback, for a total of 20 trials per subject. Trial order (with and without force feedback) was counterbalanced across the 20 trials, with each subject receiving the same presentation order.

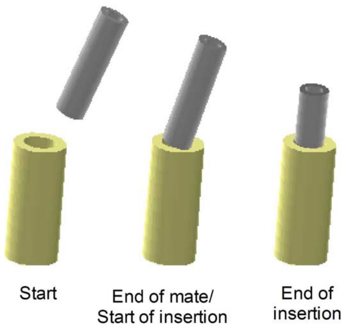


Fig. 6. Cannula insertion task showing breakdown between the mating subtask and the insertion subtask. Perspective shown is the same perspective seen by subjects, with the major axes of the tubes aligned vertically in the camera view plane.

E. Measures

All forces encountered by the instrument tip, commanded positions, commanded orientations, and trial times were recorded during each experiment at 1 kHz. Each trial was broken down into two subtasks for analysis: the mating subtask and the insertion subtask (Fig. 6). During the mating subtask, subjects attempted to position the tip of the smaller tube within the inner diameter of the second tube. Subjects were not required to match the axial orientation to complete this task. Once one part of the smaller tube was within the larger tube, the subject attempted to complete the task by matching the axial orientations of the two tubes and applying the necessary joining force. Subjects were not made aware of this task breakdown during the experiment. The trials were separated into these two subtasks because pilot studies revealed that the duration of the mating portion of the task varied significantly between trials. If subjects failed to match the tubes together in their initial attempt, repositioning the two tubes in the depth dimension took a variable length of time. The subtask boundary was recorded by the experimenter during the trial by pressing a key when the mating task was completed.

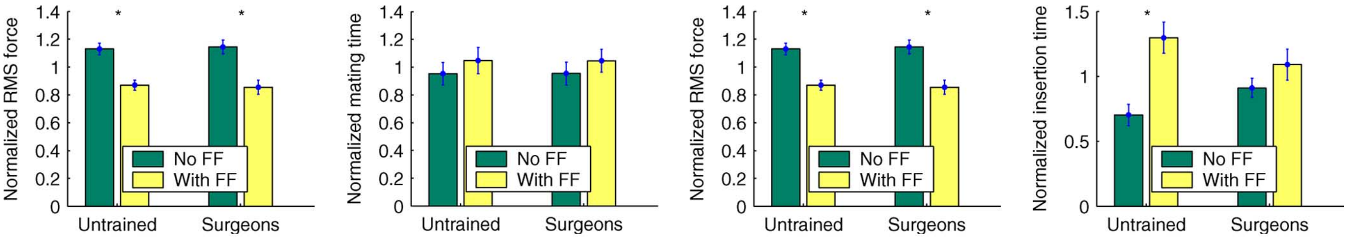
Two outcome measures were examined for each subtask to characterize the performance of a subject: the rms force applied during the subtask and the time required to complete the subtask. The rms force was calculated as the total rms force magnitude on both hands.

F. Statistical Analysis

We used a repeated measures ANOVA with a within-subject variable of force feedback condition to test for significant differences in total rms force and time for task completion. Each subtask was analyzed separately. Because a wide variation in untrained subject performance was observed in pilot studies, all subtask variables were normalized to each subject's mean across both force feedback conditions to remove intersubject variation. We used the SPSS statistical analysis software (Version 13.0, SPSS Inc., Chicago, Ill.) for all statistical tests. A p-value of less than 0.05 was considered statistically significant.

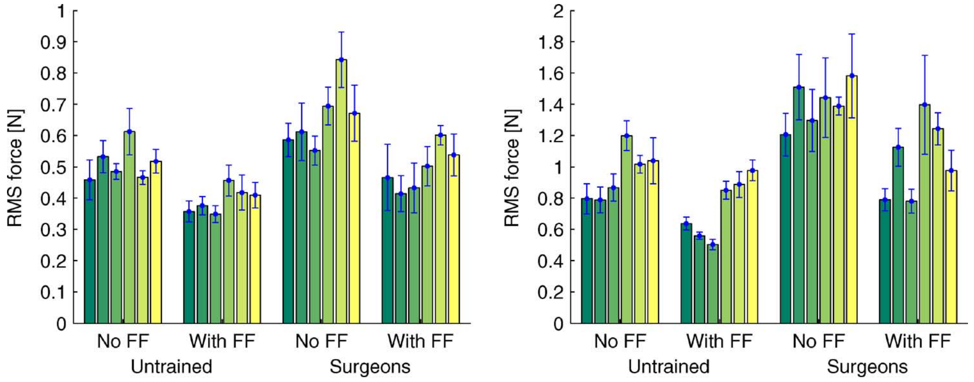
III. RESULTS

During the mating subtask, the addition of force feedback caused a reduction of rms force from 0.51 to 0.39 N in the untrained population, and from 0.66 to 0.49 N in the surgeon population. Both reductions were significant [untrained: $F(1,5) = 55.68, p < 0.002$; surgeons: $F(1,5) = 109.28, p < 0.001$] (Fig. 7(a)). Variation in rms force between subjects is less than 20% of the group mean force (across both



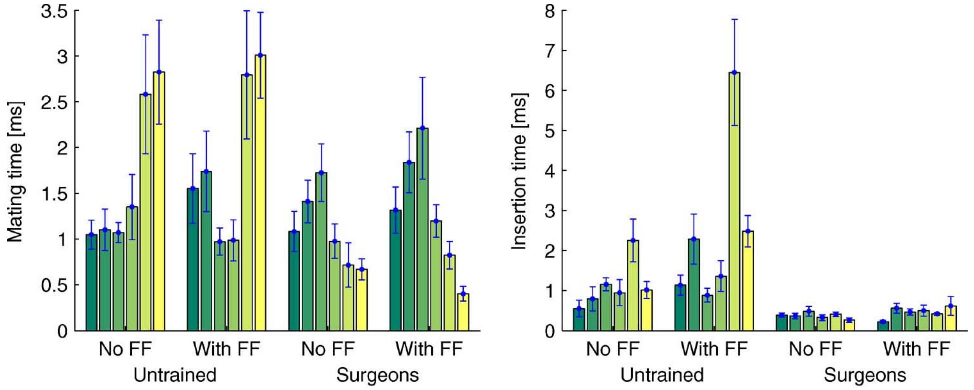
(a) (b) (c) (d)

Fig. 7. Performance metrics for mating (a and b) and insertion (c and d) subtasks. Error bars show standard error. Asterisks denote significant difference between force feedback conditions.



(a) (b)

Fig. 8. Absolute force across subjects for (a) mating and (b) insertion subtasks by training and force feedback presence. Error bars show standard error.



(a) (b)

Fig. 9. Absolute time across subjects for (a) mating and (b) insertion subtasks by training and force feedback. Error bars show standard error.

force feedback conditions), with an average 95% confidence interval of ±0.09 N (Fig. 8(a)).

Untrained subject mating times ranged from 10 to 30 s, with a group mean (across both force feedback conditions) of 17.5 s. Surgeons completed the mating subtask with average completion times from 4 to 22 s, with a group mean of 12.0 s. Force feedback caused no significant change in the time required to complete the mating subtask for either population $[F(1{,}5) = 0.651, p = 0.46; F(1{,}5) = 0.587,\ p = 0.478]$ (Fig. 7(b)). Variation between subjects was high in both populations (Fig. 9(b)).

With force feedback during the insertion subtask, rms force dropped from 0.95 to 0.74 N in the untrained population, and from 1.40 to 1.05 N in the surgeon population. This reduction in force due to force feedback was significant for both populations [untrained: $F(1{,}5) = 15.5$, $p < 0.02$; surgeons: $F(1{,}5) = 14.64, p < 0.015$] (Fig. 7(c)). Variation in rms force between subjects was higher than during the mating subtask, with an average 95% confidence interval of ±0.2 N (Fig. 8(b)).

Mean untrained subject insertion times without force feedback ranged from 5 to 22 s, with a group mean of 11.2 s. With force feedback, the group mean increased to 24.3 s, and individual mean completion times ranged from 9 to 65 s. Surgeons completed the insertion subtask with a group mean of 4.2 s, with no individual mean completion time above 7 s. The increase in time required for the untrained subjects to complete the insertion subtask was significant $[F(1{,}5) = 9.25,\ p < 0.03]$ (Fig. 7(d)), while the increase in completion time observed for the surgeon population was not $[F(1{,}5) = 0.852,\ p = 0.398]$. Variation between subjects was much higher in the untrained versus the surgeon population (Fig. 9(b)).

IV. DISCUSSION

We tested the hypothesis that the addition of force feedback to a cannula insertion task can improve performance. Cannula insertion requires the surgeon to control both position and orientation. A main result of our experiment is that force feedback decreases applied force for both untrained and surgically trained subjects. Our results further suggest that the effect of force feedback on completion time can depend on training. Only the surgically trained group decreased applied force without significantly increasing trial time.

One key distinction in the analysis of force feedback benefit is the difference between providing information versus passive physical constraints that arise when interacting with the environment [20]. The cannulation task was chosen because, with three-axis force sensing and feedback, task forces do *not* constrain the two tubes to match position and orientation. Assuming there is some compliance in the hand, the forces may push the tube to a position that causes lower overall forces, but will never correct the orientation, so there is no immediate physical constraint benefit. The cannulation task illuminates the role of force feedback as an information source. If the two tubes were mated and the subjects attempted to join them, significant interaction forces were only generated if the tube alignments were mismatched. In the presence of force feedback, subjects would feel the interaction force, signaling an incorrect alignment. If the tube deformations are large enough, a subject could derive this information from the visual field. Presumably, this information can be obtained through lower applied forces in the presence of force feedback [21].

A. *The Effect of Training*

A primary result of this study is that the type of benefit provided by force feedback may depend on previous training. We hypothesize that the training effects observed in this study are due to interactions between the force feedback information source and the visual information source. Because surgeons are trained to overcome the degraded depth perception [3] and hand–eye mismatch [19] encountered in minimally invasive surgery, they can readily integrate additional information from forces into their spatial model. Untrained subjects might lack a sufficient spatial model. Consequently, even though the force information reveals an orientation mismatch, they do not know what motions will correct the orientation. This hypothesis is supported by the known difficulty associated with laparoscopic procedures [5]. Deriving a sufficient spatial model is challenging, as demonstrated by the performance increases observed when using a 3-D display versus 2-D [22]–[24]. Training is also likely to reduce performance variation between subjects. Performance within the trained surgeon group was consistent, while there was wide variation in the untrained subject group, particularly in the insertion time.

Few studies have directly addressed the role of training in surgery with respect to performance with force feedback. Kazi demonstrated a similar reduction in applied force for a single handed telemanipulated cannulation task, but did not address whether subject training influenced the benefit of force feedback [8]. Force feedback has also provided a performance benefit in the related task of peg in hole insertion in a stiff environment (e.g., [25]). A study of a nonsurgical visual–motor task revealed that training results in a performance increase as subjects learn to incorporate the presence of forces [26]. Nonetheless, a previous study of a blunt dissection task [6] showed little difference in the qualitative performance benefit from force feedback among subjects with differing surgical training. This task, however, did not require precise orientation control. Thus, the results of the current study suggest that, although force feedback can improve surgical performance, certain tasks require that the surgeon have prior experience to fully benefit from the presence of force feedback.

There are alternative explanations for the difference between subject groups. The surgeons consistently applied more force both with and without force feedback than the corresponding untrained group. This is consistent with surgeon performance in a blunt dissection task [6]. Surgeons may have completed the insertion subtask in less time simply because they more often exceeded the force threshold necessary to overcome friction. While this certainly contributed to the training effect, it does not entirely explain the difference between groups. Two of the surgeons applied lower forces than three of the untrained subjects, yet still did not require a longer time to complete the insertion subtask in the force feedback condition. In contrast, all three untrained subjects who applied higher forces than these surgeons required more time to complete the insertion subtask with force feedback. Consequently, it appears there are at least two separate training effects that influence ability to benefit from force feedback in surgery: 1) familiarity with force levels required to complete the task, and 2) ability to interpret 3-D force cues based on a two dimensional visual field.

B. *Application to Surgery*

Surgeons were informally questioned after completion of the experiment. All surgeons responded positively regarding the force feedback, reporting that the presence of the force feedback aided performance. The opinions on how it helped, however, varied between surgeons. Some felt that the forces assisted only with the mating portion of the trials, giving quick feedback when the two tubes were near in depth, or feeling the inner edge of the tube, thus knowing the tubes were almost mated. These subjects did not report feeling any benefit of force feedback during the insertion subtask because the force feedback did not help with orientation. On the other hand, some surgeons reported no benefit of force feedback during the mating subtask, but instead reported using the force feedback during the insertion phase to determine whether the tubes were aligned based on a change in compliance.

The above observations illuminate where the addition of torque feedback would be useful. We have discussed ways in which three-axis force feedback provides information, and torque feedback can provide similar informational benefits. Additionally, torque feedback is necessary to provide a passive constraint benefit in orientation. Example applications include needle passing (matching orientations between two graspers) and suturing (passively maintaining needle orientation once the needle is partially driven). Naturally, the addition of torque feedback to a telemanipulation system would be associated with a significant increase in system cost and complexity.

A final observation as to the benefit of the three-axis force feedback in a cannulation task is that, even without torque feedback, force feedback does enable passive strategies that would not be possible with only force information (such as with sensory substitution). Knowing that there is a force threshold that needs to be exceeded for the two tubes to join, a subject can consistently apply that force and vary the position and orientation until the join is successful. This is opposed to the "guess and check" strategy employed by many of the untrained subjects, where they would attempt a join, feel the force rise (implying the position or orientation was incorrect), adjust, then reattempt. Using the passive strategy turns one of the degrees of freedom of the task (positioning along the major axis of the tubes) from a mentally intensive position control task into a relatively easy force control task. Thus, force feedback can potentially reduce mental workload of the surgeon, improving surgical success and patient safety.

V. ACKNOWLEDGMENT

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Friction Compensation for Enhancing Transparency of a Teleoperator With Compliant Transmission

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***Abstract*—This paper presents a model-based compensator for canceling friction in the tendon-driven joints of a haptic-feedback teleoperator. Unlike position-tracking systems, a teleoperator involves an unknown environment force that prevents the use of tracking position error as a feedback to the compensator. Thus, we use a model-based feedforward friction compensator to cancel the friction forces. We provide conditions for selecting compensator parameters to ensure passivity of the teleoperator and demonstrate performance experimentally.**

***Index Terms*—Friction compensation, haptic feedback, passivity, telerobotics, transparency.**

I. INTRODUCTION

The dynamic properties of the manipulators of a haptic-feedback teleoperator (Fig. 1) limit the transparency of a teleoperator in transferring forces of the environment to the operator. When an operator moves the master manipulator to direct the slave manipulator, forces of the manipulators due to inertia and friction resist the operator's motion. These forces contribute to the operator's fatigue and mask small forces between the slave manipulator and the environment.

Ideally, force sensors can be used to eliminate resistant forces of the manipulators from being fed back to the human operator [1], but

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