Analysis of Suture Manipulation Forces for Teleoperation with Force Feedback

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Abstract. Despite many successes with teleoperated robotic surgical systems, some surgeons feel that the lack of haptic (force or tactile) feedback is detrimental in applications requiring fine suture manipulation. In this paper, we study the difference between applied suture forces in three knot tying exercises: hand ties, instrument ties (using needle drivers), and robot ties (using the da Vinci™ Surgical System from Intuitive Surgical, Inc.). Both instrument and robot-assisted ties differ from hand ties in accuracy of applied force. However, only the robot ties differ from hand ties in repeatability of applied force. Furthermore, comparison between attendings and residents revealed statistically significant differences in the forces used during hand ties, although attendings and residents perform similarly when comparing instrument and robot ties to hand ties. These results indicate that resolved force feedback would improve robot-assisted performance during complex surgical tasks such as knot tying with fine suture.

1 Introduction

Robot-assisted surgical systems are enhancing the ability of surgeons to perform minimally invasive procedures by scaling down motions and adding additional degrees of freedom to instrument tips. Thousands of general surgeries and several hundred cardiac surgeries have been performed worldwide with teleoperated robotic surgical systems [1]. Moreover, both the ZEUS® Surgical Robotic System from Computer Motion (Goleta, CA) [2, 3] and the da Vinci™ Surgical System from Intuitive Surgical, Inc. (Mountain View, CA) [4-8] have been used in cardiac surgery to perform coronary artery bypass grafting and mitral valve repair [9]. Despite these successes, many surgeons claim that further progress in this field is limited by an unresolved problem: the lack of haptic (force and tactile) feedback to the user. This is especially detrimental in fields where force is applied to fine suture and delicate tissues, such as cardiac surgery. Appropriate applied forces are critical in creating knots that are firm enough to hold, but do not break sutures or damage tissue.

Until now, the problem of the lack of force feedback has only been described anecdotally. The goal of this work is to quantify the effect of force feedback on performance in a suture manipulation task. This will allow us to determine whether bilateral

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telemanipulation with force feedback would improve performance in applied force accuracy and repeatability. A bilateral telemanipulation system provides bilateral interaction between the robot and the user: the user specifies the robot motion using the master, and also feels resolved forces that are sensed by the robot.

It is important to distinguish between haptic, tactile, and force feedback. Haptic information is a broad term used to describe both cutaneous (tactile) and kinesthetic (force) information. Both types of information are necessary to form the typical sensations felt with the human hand. In this paper, we consider force feedback, where forces are resolved to a single point, and are displayed to the user through a tool. A haptic device such as the Phantom from SensAble Technologies (Woburn, MA) [10] can provide this type of feedback. The master of the da Vinci™ is also equipped to provide force feedback, although currently little to no feedback is provided. Tactile display devices are not yet commercially available, and are not likely to meet the size and weight constraints for multi-degree-of-freedom systems in the near future.

1.1 Previous Work

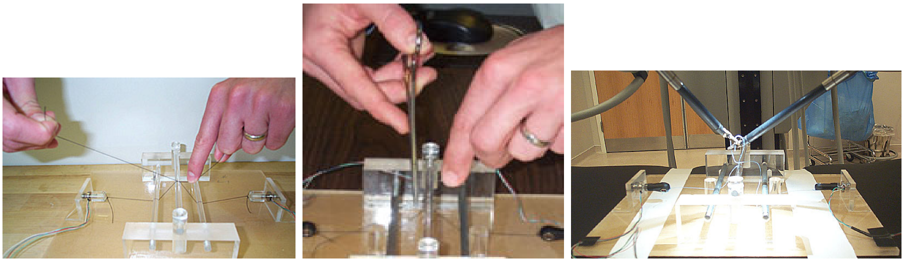
Although a significant effort has been put forth in motion analysis, e.g. [11], little work has focused on characterizing the forces resulting from surgical tasks. Force feedback in teleoperated systems is known to improve the performance of a user in some situations [12, 13]. Moreover, the "addition of kinesthetic force feedback is of substantial help in moving performance toward the extreme demonstrated by the bare-handed human" in a force-reflecting teleoperated system [14]. In addition, Rosen, et al. showed that bilateral telemanipulation of an endoscopic instrument returned haptic information that was lost when a surgeon manipulated soft tissues using a traditional endoscopic tool/grasper. [15].

However, there exists some anecdotal evidence against the use of bilateral telemanipulation in a suturing task. In [16], the tip forces of the robot were indirectly sensed using actuator torques. Using this sensing method during robot-assisted suturing, it was found that force feedback "was more of an annoyance than a help." It is suspected that the tip forces were not appropriately sensed; without a comprehensive study, one cannot characterize the appropriate resolution and distribution of force sensors, or the change in performance when force feedback is provided.

2 Experiments

The experiments were designed to evaluate three claims:

1. *Accuracy*: The force magnitudes applied with the needle driver are indistinguishable from those applied solely by hand, while the forces applied with the robot are different from those applied by hand. This claim seeks to show that forces can be applied more accurately with resolved force feedback than without.
2. *Repeatability*: The normalized standard deviation of force (standard deviation as a percentage of the average force level) for instrument ties is indistinguishable from hand ties. However, the normalized standard deviation for robot ties is different from that of hand ties. This claim intends to demonstrate that forces can be applied with better repeatability with the instrument than with the robot.



(a) (b) (c)

Fig. 1. A tension measurement device is used to measure the forces applied to sutures, (a) by hand, (b) by instrument, and (c) using the robot

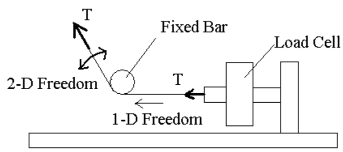


Fig. 2. Side view of the measurement device. The pulling force in two dimensions is resolved into the direction parallel to the axis of the load cell. This design allows users to perform the task in a natural way even though the measurement device has only one degree of freedom

3. *Skill Comparison*: Residents have higher normalized standard deviations than attendings for hand ties and instrument ties. With the robot, there will be a reduction in performance margin between the two groups.

2.1 Experiment Design

Complex surgical tasks, such as knot tying, require force feedback. In practice sessions with the robot, novice users occasionally broke fine polypropylene sutures during the first throw of a knot. In our experiments, we measured the tension applied to sutures during the first throw of a knot by the left and right hand using a tension measurement device (Figure 1). The device consists of two one-degree-of-freedom Entran® load cells tied to sutures, and bars used to orient the applied force in the direction parallel to the axes of the load cells. The device design made it possible for users to perform the task in a natural way and to record the tension in the suture (Figure 2). Separate sutures were used for the left and right hands, and each suture was replaced after 5 ties. While data was acquired for both hands, only the dominant hand (the right hand for all the subjects) was used in data analysis.

Three conditions were used, as shown in Figure 1. The first condition was a hand tie, representing the feedback received by a surgeon during traditional execution of a procedure. The second condition was an instrument tie, which is commonly used in procedures where it is difficult for the surgeon to access the suture by hand. The instrument tie mimics the type of feedback a surgeon would receive through a resolved-force haptic interface. Thus the performance during an instrument tie is used as an estimate of performance with ideal bilateral telemanipulation. As shown in the figure 1 (b), the instrument was used only on the right hand side, which was the dominant hand for all subjects. The third condition used the da Vinci™. In this final condition, the surgeon observed a magnified, three-dimensional display from the endoscope. In the other conditions, the surgeon could directly observe the suture.

Six surgeons, four attendings, and two residents performed the hand, instrument and robotic ties. Of the attendings, one had performed over one hundred nissen fundoplications and splenectomies with the robot, two had over 5 hours of experience with the robot (tying sutures on phantoms), and one had not used the robot before. The two residents had less than 1 hour of previous experience with the robot. Six different sutures used in general and cardiac surgeries were employed in this experiment. The sutures, which varied by type and size, were: 2-0 Silk, 2-0 Ti-Cron, 4-0 Polypropylene, 5-0 Polypropylene, 6-0 Polypropylene, and 7-0 Polypropylene from various manufacturers (e.g., Ethicon, USSC and Sherwood-Davis & Geck). Five tension recordings were taken for each suture used by each surgeon. The data set for one subject, an attending, is provided in Figure 3.

A total of 30 throws were recorded for each surgeon under a single condition (hand, instrument, or robot). The testing for hand and instrument were performed together for four of the six subjects, and the other two subjects separated their hand and instrument ties by at least one day. The robot experiments were performed at least one week later for all subjects. The task was to perform a single throw of a knot in standard fashion around a circular rod in the middle of the tension measurement device. The subjects were instructed to aim for consistency and accuracy in applied force, rather than speed of completion. In addition, the subjects were asked to hold the throw for three seconds at the desired tension level.

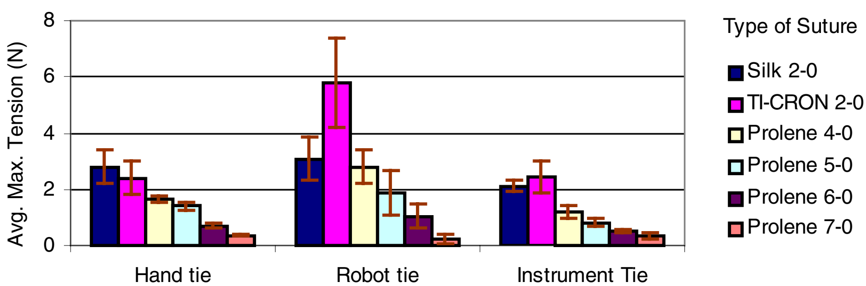


Fig. 3. Data summary for a single subject (attending surgeon). The forces applied to various sutures change with suture strength. For this subject, the instrument tie force levels and standard deviations of the hand tie and instrument tie are similar, while those of the robot tie are different

2.2 Data Segmentation

The data obtained was force applied to the suture for the left and right hands. The tension data was plotted against time for each run (one run is shown in Figure 4). The graph consists of 3 active regions: (a) increasing tension, (b) holding tension, and (c)

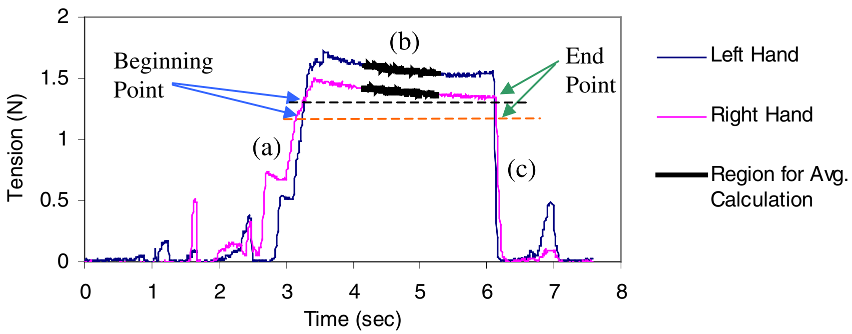


Fig. 4. Data recorded from a single throw. The data is segmented into three areas: (a) increasing tension, (b) holding tension, and (c) decreasing tension. The average of forces in the middle 40% of the holding region is used in data analysis

decreasing tension. The holding region was automatically segmented from the other two regions at points that were 90 percent of the maximum tension measured during each run. The middle 40 percent of the holding region was the only portion of the data included in the calculation of the average applied tension for each run. From Figure 4, it is clear that different forces are used for the two hands, which is possible because forces were measured on two separate sutures. In practice, the left and right hand forces in a single suture can also differ due to friction between the suture and the tissue, or the suture and itself. The tension measurement device was designed to minimize friction.

2.3 Results

For each of the three claims described previously, the Student's t-test was used for data analysis. We will now describe the results and implications of these three claims individually.

Claim 1: Accuracy. The first claim was that the instrument ties would produce the same applied tension as the hand ties, whereas the robot-assisted ties would not. First, we compared the means of the forces applied during hand and instrument ties for each user and each suture (n= 30). The number of these comparisons with a p-value of greater than 0.1 was 19, meaning that 63.3% of the trials showed that there is a difference between the instrument tie and the hand tie. Second, we compared the means of the forces applied to hand and robot-assisted ties for each user and each suture (n=30). The number of these comparisons with a p-value greater than 0.1 was 22, meaning that 73.3% of the trials showed that there is a difference between the robot tie and the hand tie.

These results indicate that forces used for instrument ties are slightly better than robot ties, when the goal Is to apply the same force as for hand ties. However, this difference is not large enough to conclude that accuracy would be improved to the level of hand ties with the inclusion of resolved-force feedback (which would feel similar to the instrument tie) in a robot-assisted surgical system. Therefore, Claim 1 cannot be validated.

Claim 2: Repeatability. The second claim was that the normalized standard deviation (NSD) of forces for instrument ties are indistinguishable from the hand ties, and that the NSD of forces for the robotic ties are different from the hand ties. In this case, the data for comparison was the average normalized standard deviation for each subject. First, we compared the mean hand ties NSD to the mean instrument ties NSD for each user. The number of these comparisons with a p-value of greater than 0.1 was 0 (n= 5), meaning that none of the subjects demonstrated a difference between instrument ties and the hand ties. Second, we compared the mean hand ties NSD to the mean robot ties NSD for each user. The number of these comparisons with a p-value of greater than 0.1 was 3 (n=5), meaning that 60.0% of the subjects demonstrated a difference between robot ties and hand ties.

These results indicate that instrument ties provide an NSD more similar to the hand ties than do the robot ties. The hand tie had the lowest NSD of all methods. We can conclude that this claim is satisfied; repeatability would be improved with the inclusion of resolved force feedback (which would feel similar to the use of an instrument) in a robot-assisted surgical system.

Claim 3: Skill Comparison. The third claim was that, while residents have higher NSD than attendings for hand ties and instrument ties, the robot significantly mitigates this difference. In our group of subjects, the residents had significantly less surgical experience than the attendings, so one can also consider these groups to be "novice" and "expert." This experiment consists of three different tests comparing resident and attending by: (1) hand ties, (2) instrument ties, and (3) robot ties. Our results demonstrate a significant difference in hand ties (p=0.03), however, no statistically significant difference was demonstrated for instrument (p=0.40) or robotic (p=0.25) ties. Thus, this claim is not satisfied because both the instrument and the robot reduce the performance margin between expert and novice users.

3 Discussion

The goal of these experiments was to examine claims about the necessity of force feedback for robot-assisted surgical systems. All of the claims were partially satisfied in that user performance (both accuracy and repeatability) for robot ties was worse than user performance for hand ties. However, the claims also purported that the application of force feedback to the user would eliminate these differences, and this was not always found to be true.

There has been much discussion in the robotics and medical communities about the application of force feedback to robot-assisted surgical systems, and this work provides the first statistically significant data indicating that doing so may not enhance performance to the level of direct manual operation. When surgeons manipulate sutures by hand, some local tactile information is being used to sense suture tension, even when a surgical glove mediates the forces. It is possible that this tactile information is critical to maintaining accuracy and repeatability in the application of suture forces, since tactile sensation is very important in exploration and manipulation [17].

Unfortunately, practical application of such tactile feedback to teleoperated systems is not likely to happen in the near future.

Since current robot-assisted surgical systems continue to be limited by a lack of haptic feedback, a form of sensory substitution may be a short-term solution. By using data obtained from the hand ties as the standard, one could create a system where the current and desired amounts of tension applied to suture can be displayed to the surgeon. This would facilitate the accomplishment of complex surgical tasks such as knot tying. This study represents an initial step, and further research is needed before appropriate feedback can be relayed to the surgeon.

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