Effect of Backlash on Surgical Robotic Task Proficiency

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Abstract—Teleoperated surgical robot designs, particularly those utilizing cable drive mechanisms, often exhibit motion backlash. This paper presents an experiment that investigates how backlash affects proficiency in basic surgical skills. Backlash was added to the Laprotek surgical robot using software, and subjects completed three Fundamentals of Laparoscopic Surgery (FLS) tasks. Three subjects performed the tasks under five different levels of system backlash (1, 5, 10, 15, and 20 mm). Subjects were able to complete the tasks with all levels of backlash. A linear relationship was observed between the amount of backlash in the system and task completion time. On average, completion times increased by 5% for every 1 mm of additional backlash in the system.

I. INTRODUCTION

Teleoperated surgical robots play an important role in surgery today and show tremendous potential for future growth. The da Vinci Surgical System from Intuitive Surgery (Sunnyvale, CA) [1] has been used to perform the vast majority of robotic cases to date. This system improves the precision and dexterity of surgery due to the teleoperated architecture and articulated instruments, but it follows the existing paradigm of standard laparoscopic surgery using straight instruments that pivot about the incision.

Next-generation surgical robots look to improve on this design and expand into other potential application areas and surgical specialties. Several researchers are working on smaller more modular designs that mount to the operation room table and reduce the size and complexity of the patient-side manipulators [2]-[5]. These systems could reduce the overall cost of robotic surgery and improve hybrid procedures using a combination of manual and robotic instruments. Other surgical robots under development are moving away from the structure of rigid tools to utilize long flexible instruments that can access tissue through a single port or natural orifice. Some of these robots will enable less invasive endoluminal surgery in the gastrointestinal tract [6]-[7], subxiphoid access to the heart [8], and interventional-radiology based cardiac surgery within the heart [9].

Due to space constraints, many of these next-generation systems use cable-conduit drive mechanisms to transmit motion from remotely located actuators through curving pathways to the surgical site within the body. This actuation mode provides significant benefits of simplified transmission, reduced joint mass and flexibility of actuating shaft, but it also introduces nonlinearities due to compliance of the actuation cables and friction within the conduit. The combination of these factors often results in a noticeable backlash in the motion when the instrument changes direction [10]. In a teleoperated system, this backlash appears to the operator as a dead zone where small motions of the master interface controller result in no motion of the slave instrument tip. This can result in a loss of precision and increased complexity of performing surgery. Minimizing backlash is therefore identified as an important system design goal when developing a new surgical robot system.

While addressing these nonlinearities, Kesner and Howe [9] have demonstrated that careful mechanical design combined with a model based backlash inverse in the control could reduce tracking errors of a robotic catheter system to under 1 mm. Similarly, Agrawal et al. [11] demonstrated an adaptive backlash inverse controller that could dynamically estimate model parameters and compensate for changes in friction caused by changes in conduit curvature during use. Both of these approaches were able to eliminate much of the backlash in the system but require real-time measurement of the output tip position, which is not always possible for many surgical robotic applications. In these cases, the designer is challenged with a fundamental question: How much backlash can the surgical robot have before the nonlinearity significantly degrades a surgeon’s ability to perform surgery? This paper presents an experimental study to help answer this question.

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Fig. 1. FLS Peg transfer Task being performed with the Laprotek Teleoperated Surgical Robot. Varying levels of backlash were added through software to the desired X-Y-Z instrument tip positions.
Using the Laprotek surgical robot, subjects performed basic surgical skill tasks under varying levels of software-induced backlash. The experimental protocol follows a similar approach used by Lum et al. who studied how completion times for skills tasks varied with the amount of time delay present in the teleoperated feedback loop [12]. To provide a standardized method and common reference frame between researchers, they used a peg transfer task based on the Fundamentals of Laparoscopic Surgery (FLS) training program created by the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) [13]. Following this lead and the research of Ma and Berkelman [4], the experiment presented here uses three of the five FLS tasks (peg transfer, precision cutting, and intracorporeal suturing) to investigate the qualitative and quantitative effects of backlash on the proficiency of fundamental surgical skills.

II. METHODS

A. Laprotek Surgical Robotic Platform

The Laprotek System used in the experiments (Figs. 1-5) is a modular, teleoperated surgical robot platform developed by one of the authors at EndoVia Medical (formerly located in Norwood, MA) and clinically validated in 11 human cholecystectomy procedures [14]. The base system consists of a surgeon console and two patient-side manipulators that mount to the rails of the OR table (Fig. 2). It permits bimanual manipulation of wristed instruments within the abdomen through standard laparoscopic ports with a motion scaling factor of 3 to 1.

The surgeon console (Fig. 3) contains the main electronics, 2D visualization monitor, and two seven-degree-of-freedom (DOF) input control arms used to drive the robotic instruments. The input control arms mimic the structure and motion of the operator’s arm to provide a full range of motion and avoid singularities of the gimble. Each handle contains a finger paddle to control the instrument jaw motion and a thumb button to allow “clutching” of the handle position and navigation of the GUI during operation. All 7 DOF of the arm are actuated to provide gravity compensation and haptic feedback.

The Laprotek patient-side manipulator and instruments are shown in Figs. 1 and 5. They consist of a motor pack mounted to the OR table rail with flexible cable/conduit pairs that transmit motion to the robotic positioning arm located above the patient in the sterile field. A passive articulated support arm holds the robotic arm in place and allows alignment of the mechanism’s remote center of motion (RCM) with the incision.

The robotic positioning arms and instruments provide a full 6 DOF plus jaw motion. The axes of motion are indicated by the numbers in Fig. 5. Axis 1 causes the instrument to pivot left and right about the incision. Axis 2 is a linear joint that translates the instrument in and out of the incision. Axis 3 creates the vertical motion of the instrument tip by rotating the curved “guide tube” through the incision. An advantage of this design is that the instrument tip can be fully positioned by moving the proximal end of the robotic arm only in a plane, which minimizes the swept volume in the sterile field [2].

The disposable instruments fit through the curved guide tube and can be easily exchanged during a procedure to allow a variety of instrument jaws to be used (grasper, dissector, cautery hook, scissors, and needle driver). The orientation of the instrument end effector is created by rotating the flexible shafted instruments within the guide tube (Axis 4) and articulating the distal wrist (Axes 5 and 6).
Fig. 5. Laprotek patient-side manipulator and axes of motion. Cable conduit pairs transmit motion to the robotic arm from the motor pack. Joints 1-3 create motion about the remote center of motion (RCM) located at the skin incision. Joints 4-6 create the desired orientation of the end effector.

B. Laprotek Baseline Performance

As a first step in the experimental design, it was critical to optimize the baseline performance of the Laprotek robot and minimize backlash as much as possible. An initial evaluation of the Laprotek was conducted by Dachs [15]. He found that the backlash of the slave joints was greatly diminished by implementing a model based backlash inverse within each joint control, but the amount of correction was limited by the fact that backlash levels changed depending on the total curvature of the cable conduits from the motor pack. Therefore in this experiment, the shape of the conduits was carefully controlled by holding the slave arms fixed with a rigid support frame. The backlash inverse was then optimized for each joint in this configuration.

After optimization, the joint level backlash was measured by commanding a sinusoidal trajectory in the joint space and recording the resulting output motion using a 6-axis position sensor (3D Guidance trakStar, Ascension Technologies, Burlington, VT; 0.5 mm and 0.1° RMS resolution). Table 1 reports the results from these tests.

Due to the kinematic configuration of the robot, the overall backlash in the system as observed by the surgeon is a complex combination of the backlash of the individual joints. For example, purely lateral motion of the Laprotek instrument tip requires a coordinated motion of Axes 1 and 2. To quantify this, the overall backlash levels in the XYZ directions were measured by commanding a sinusoidal desired tip position in each direction from the zero position shown in Fig. 5 and recording the actual motion using the 6-axis position sensor. A similar experiment was conducted for the orientation of the instrument tip by commanding a sinusoidal motion for the roll, pitch and yaw rotations. Table 2 summarizes the results from these tests. Based on these measurements, the overall backlash for the Laprotek system used in the experiment is approximately 1 mm in the XYZ directions and 5° in orientation.

C. Software-Induced Backlash

To simulate various levels of backlash in the system, the performance of the Laprotek robot was degraded through software by introducing backlash into the desired tip position (XYZ) of the slave robot. For this initial experiment, the induced backlash was added to the XYZ tip position relative to a global reference frame rather than to the desired joint positions. Although this “Cartesian” style of backlash is difficult to realize physically, it provides a more universal result that is independent of the kinematic structure of the Laprotek robot. To further simplify the experimental results, the induced backlash distance was made equal in the X, Y, and Z directions resulting in an axis aligned cube.

Based on initial testing and the relative scale of laparoscopic surgery, five levels of induced backlash were implemented in the software for the experiment: 1, 5, 10, 15, and 20 mm. The 1 mm backlash represents the baseline performance of the Laprotek as described above. The other backlash levels represent a combination of the induced backlash plus the baseline. The five backlash levels were verified by commanding a 0.2 Hz sinusoidal motion in desired instrument tip XYZ positions and measuring the actual tip position using a 6-axis position sensor. Fig. 6 shows the recorded output motions for the X direction versus time for two cycles of motion. The different backlash levels are clearly visible in the command versus output trajectories shown in Fig. 7. Similar results were collected for the Y and Z directions.

<table>
<thead>
<tr>
<th>Approximate Lever Arm from RCM</th>
<th>Joint Backlash</th>
<th>Resulting Backlash at Tip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axis 1 200 mm</td>
<td>0.25°</td>
<td>0.9 mm</td>
</tr>
<tr>
<td>Axis 2 -</td>
<td>0.7 mm</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Axis 3 65 mm</td>
<td>0.70°</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Axis 4 -</td>
<td>2.4°</td>
<td>2.4°</td>
</tr>
<tr>
<td>Axis 5 -</td>
<td>3.9°</td>
<td>3.9°</td>
</tr>
<tr>
<td>Axis 6 -</td>
<td>4.3°</td>
<td>4.3°</td>
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<tr>
<th>Measured Overall Backlash in Laprotek Slave</th>
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<tbody>
<tr>
<td>X</td>
</tr>
<tr>
<td>1.0 mm</td>
</tr>
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Fig. 6. Measured output motion in the X direction for the 5 levels of induced backlash based on a ±20 mm sinusoidal desired trajectory in the X direction.

Fig. 7. Input-output plot of the data shown in Fig. 6, showing the hysteresis curves for the 5 levels of backlash tested in the experiment.

D. Experimental Design

Three of the five FLS training tasks were used in this experiment to evaluate the effect of backlash on proficiency of basic robotic surgical skills: (1) peg transfer, (2) precision cutting, and (3) intracorporeal suturing. Subjects completed these tasks using the Laprotek robot with the five levels of induced backlash discussed earlier: 1, 5, 10, 15, and 20 mm. Proficiency was determined by the time required to complete each task.

Three subjects with no medical training participated in the study. The subjects included two males and one female, all right hand dominant with an average age of 33 years. The subjects had varying levels of experience with the surgical robot. Subject 1 was the most experienced with more than 100 hours of operating time on the system. Subject 2 had a moderate experience of approximately 10 hours, while subject 3 had a one hour training session on the system prior to the experiment.

Subjects were instructed to complete each task as quickly as possible without error. Potential errors included dropping a block during transfer, cutting outside the two circles drawn on the gauze, or failing to tie a proper tight knot. In addition, the accuracy of the suture placement relative to the entry and exit dots on the Penrose drain was measured.

Subjects were tested on one task at a time. To begin, they were allowed to practice the task on the baseline system with no added backlash until they felt comfortable and had optimized their technique. The subjects then performed the task at each of the five backlash levels, considered a “set”. The order of the backlash levels in a set was randomized. To account for learning effects, subjects completed sets until their times stabilized at all five backlash levels. Subjects then performed 5 more sets which were used to calculate the resulting data. Subjects were given a short break in between trials and a longer break between sets. The data was collected over multiple days within a 7 day period.

All three subjects completed the peg transfer and precision cutting tasks. Due to varying experience levels between the subjects, only Subject 1 was able to complete the intracorporeal suturing task. Training times also varied between the subjects due to experience level. Subjects 1 and 2 required three to five training sets before completion times stabilized, while Subject 3 required 9 training sets to develop a consistent technique with the precision cutting task.

III. RESULTS

All three subjects were able to complete the FLS tasks they attempted at all five levels of backlash within the maximum time limit specified by the FLS guidelines. The variation of measured completion times with backlash levels are summarized in Figs. 8 and 9. The diamonds and error bars in the plots represent the mean and standard deviation of the five trials performed at each backlash level.

For the peg transfer task, average completion times were similar for all three subjects at the 1 mm backlash level (126.2, 125.6, and 113.6 s for subjects 1, 2, and 3 respectively). Completion times increased for each subject as backlash level was increased in the system. The relationship between these variables was observed to be approximately linear, as shown by the least-squares fit in the plots. The slope of the line indicates the effect of the backlash on the subject. For this task, Subject 2 was least affected by the backlash with the lowest slope (4.64 s/mm) and was the most consistent between trials. Subject 3 was more inconsistent and had the highest slope (8.47 s/mm).

Combined, subjects committed only 3 errors on this task, which were unrelated to backlash level.

Precision cutting was a more difficult task and therefore differentiated by the subject’s experience level. Subject 1 had the fastest times and was least affected by the backlash (slope of 2.37 s/mm). Subject 2 was slightly more inconsistent with higher completion times. Subject 3 was significantly slower at this task with more variability, but still showed a linear increase between completion time and backlash. All three subjects were able to cut within the circle lines for all trials.
The intracorporeal suturing task was only performed by Subject 1. Despite the complexity of the task and precision required, the results follow a trend similar to the other tasks (Fig. 9). The subject successfully completed the task at all backlash levels and showed a linear relationship between completion time and backlash distance. The number of errors committed during the task did not change with backlash, and suture placement was consistently within 1 mm from the entrance and exit dots.

A statistical analysis was performed for each task within a subject using a one-way ANOVA. The results indicated that the variation in completion times was statistically significant relative to backlash for all three tasks and subjects ($p<0.001$ and $F>17$ for all cases). Due to the difference in the tasks and the subjects experience level, we did not compare the subjects or tasks against each other. An additional analysis was done using t-tests to compare the five individual backlash levels within a subject for each task. Only three of the seventy t-tests computed were not statistically significant ($p>0.05$): the 10 and 15 mm backlash levels for Subject 3 on the peg transfer task, the 5 and 10 mm backlash levels for Subject 1 on the precision cutting task, and the 15 and 20 mm levels for Subject 2 on the precision cutting task.

### Table 3

<table>
<thead>
<tr>
<th>Subject</th>
<th>Task Description</th>
<th>Y Axis Intercept (S)</th>
<th>Slope (S/mm)</th>
<th>Normalized Slope* (% per mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1 – Peg Transfer</td>
<td>115.9</td>
<td>6.73</td>
<td>5.8 %</td>
<td></td>
</tr>
<tr>
<td>Subject 2 – Peg Transfer</td>
<td>117.0</td>
<td>4.64</td>
<td>4.0 %</td>
<td></td>
</tr>
<tr>
<td>Subject 3 – Peg Transfer</td>
<td>100.1</td>
<td>8.47</td>
<td>8.5 %</td>
<td></td>
</tr>
<tr>
<td>Subject 1 – Precision Cutting</td>
<td>65.6</td>
<td>2.37</td>
<td>3.6 %</td>
<td></td>
</tr>
<tr>
<td>Subject 2 – Precision Cutting</td>
<td>76.7</td>
<td>2.65</td>
<td>3.5 %</td>
<td></td>
</tr>
<tr>
<td>Subject 3 – Precision Cutting</td>
<td>92.0</td>
<td>5.10</td>
<td>5.5 %</td>
<td></td>
</tr>
<tr>
<td>Subject 1 – Suturing</td>
<td>74.7</td>
<td>2.72</td>
<td>3.6 %</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>4.9 %</td>
<td></td>
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</table>

* Normalized slope was calculated as slope divided by estimated time taken at zero backlash (i.e. Y Axis intercept)
IV. DISCUSSION

Nonlinearities in teleoperated robots are often overcome by the human operator’s ability to develop sophisticated models of the system in their brain and shape their input motions to compensate. We observed this behavior in this experiment as subjects learned to overcome the backlash in the system. When the subjects encountered a dead zone due to backlash, they would simply continue to move their hand in the desired direction until the slave instrument started tracking their motion again. This occurred consistently in every direction of motion and was independent of the amount of backlash. Higher levels of backlash simply required more motion of the master through the dead zone. Even though 20 mm of backlash is significant relative to the scale of laparoscopic surgery, using this approach the subjects could still accurately control the robot to complete the FLS tasks.

This compensation approach can also provide an explanation of the linear relationship between task completion times and backlash level. We observed that as subjects push through the dead zone, they maintain a relatively constant hand speed – independent of the width of the backlash. This means that the larger the backlash, the more time they spend moving through the dead zone. This extra time adds to the overall task completion time and would increase linearly with backlash width.

This result can be generalized by normalizing the regression slope of the trend lines shown Figs. 8 and 9 using the Y Axis Intercepts for each line, which represents the time required to complete the task with no backlash in the system. This “normalized slope” is therefore the percentage increase in the completion time per mm of backlash in the system. Table 3 shows the computed normalized slopes for each subject and task. Based on averaging this data over all of the conditions tested, we found that task completion time increased by approximately 5% per mm of backlash in the system with a 3 to 1 motion scaling factor.

Based on comments from the subjects, we also observed that completing a task with higher backlash levels required more concentration thereby elevating mental workload. Zheng et al. [16] have shown that lowering mental workload while performing basic surgical tasks improves a surgeon’s ability to handle complex situations during a procedure. Therefore, even though the subjects in this experiment were able to complete the FLS tasks with 20 mm of backlash within the required time limits, it does not necessarily mean it can be tolerated in surgery.

V. CONCLUSION

This experiment demonstrated that subjects were able to effectively perform basic FLS skills using a surgical robot with up to 20 mm of backlash present in the system. Increased backlash was found to lengthen the task completion time but did not decrease the precision of the operator while performing intricate tasks such as precision cutting or suturing. In addition, a linear relationship was observed between the level of backlash and completion time of the tasks for all subjects of varying skill levels. This observation highlights the human operator’s tendency to adapt to nonlinearities, and suggests that even substantial nonlinearities might be acceptable in some situations. However, to minimize the stress levels and operating times, lower levels of nonlinearities are desirable.

REFERENCES