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DETERMINATION OF SURGICAL ROBOT TOOL FORCE REQUIREMENTS THROUGH TISSUE MANIPULATION AND SUTURE FORCE MEASUREMENT

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ABSTRACT

Through the use of a cadaveric porcine model, forces necessary for manipulation of the abdominal organs were evaluated using an instrumented probe. Additionally, forces for tissue puncture, knot tightening, and suture breakage have been measured in order to determine the requirements placed upon the design of novel robotic surgical tools. The break forces for a variety of suture sizes and types were evaluated including sizes 3-0 through 7-0 polypropylene, size 1 polybutestor, size 4-0 chromic gut, and size 6-0 braided polyester. Tests of the tissue puncture force and knot tightening forces were carried out using the same instrumented probe, while the suture break forces were measured using a tension testing machine. The measured forces were found to compare well against the literature and provide a good basis from which to design robotic surgical tools with the appropriate capabilities.

INTRODUCTION

Surgical robots have allowed surgeons to perform a variety of procedures using less invasive techniques. These new techniques make it possible to minimize or even eliminate post-operative pain, scarring, or other complications. Further, the advent of robotic surgical tools allow for the inclusion of technologies such as force-feedback to better inform the surgeon and enable greater performance [1].

It has been shown that expert surgeons exert much less force on the tissue when compared with novice surgeons. However, it is important to understand the forces necessary to perform a particular surgical task for both the proper design of surgical tools and to minimize the potential for tissue damage [2–4]. Through experimental evaluation of these surgical tasks, it is possible to develop a better understanding of the force limitations and better define the force requirements.

Previous work in this area has quantified surgical forces in terms of both suture knot holding strength and suture tightening, as well as in the quantification of the forces associated with tissue puncture with a scalpel blade or needle [5–9]. However, the results of these studies show a wide range of variability in the measured forces due to the selected organ, the methodology, and the inherent nonlinear biomechanical properties of soft biological tissues. Thus, a better understanding of the forces associated with specific surgical tasks is necessary. Particularly, the forces associated with suturing, including suture needle tissue puncture and the force necessary to break the suture needle away from the

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suture line, has not been well characterized previously. In addition, little work has been done to quantify the forces necessary for manipulation of the abdominal organs. The general assertion is that the biological tissue should be handled in such a way to minimize the potential for tissue damage [10]. However, these forces need to be quantified to facilitate the design and development of surgical instruments.

Though there are a variety of tasks common to surgical procedures, manipulation of the abdominal organs and suturing were selected for evaluation of their force requirements as part of the present study. These tasks were selected due to their widespread applicability to a wide variety of surgical procedures and their likelihood of having greater tool force requirements. Further, in the case of suturing, the force capability of the surgical robot can affect the quality of the knot and its ability to perform as designed [5]. These results will help to define the expectations placed on novel surgical tools for procedures involving soft biological tissues.

METHODS

In order to determine the tool force requirements, a Nano25 six-axis transducer (ATI Industrial Automation) was mounted between a handle and probing tip to provide an intuitive interface for force measurement that could be used in the operating room. Through a collaboration with The Visible Heart Laboratory, access to a cadaveric porcine model was possible, which enabled measurement of the forces necessary for abdominal tissue manipulation. Abdominal tissues including the liver, spleen, gallbladder, stomach, kidney, and bladder were examined by using the force probe to manipulate the tissue such as may be necessary during surgical intervention. The force was recorded as a force magnitude applied to the tip of the probe. Then the peak value was selected from the data set for each organ and reported. In each case, the organ was manipulated in order to gain access to the underlying tissue or surrounding organs. Care was taken to avoid damaging the tissue by using the minimum force necessary to move the organ, in accordance with the practice of minimizing the potential for tissue damage as suggested in the literature [10]. As can be seen in Figure 1, the abdomen was open during the testing, which would be similar to the conditions during surgery when the abdomen is inflated.

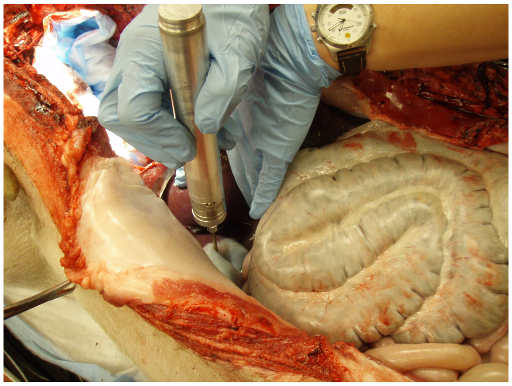

FIGURE 1. FORCE MEASUREMENTS BEING TAKEN IN A PORCINE ABDOMEN.

Using the same instrumented force probe, results were also collected for common suturing tasks such as tissue puncture and knot tightening, seen in Figure 2, where high tool force requirements would be expected. Both porcine liver and gallbladder tissues were used for needle puncture force measurements. The suture needle was passed through the tissue as would be done for a normal suturing procedure. Further, suture knot tightening forces were measured using both size 0 (3.5 metric) and size 4-0 (1.5 metric) polypropylene (Surgilene, Davis & Geck) sutures. The suture lines were pulled, and the tension in the line measured, until a satisfactory knot was formed. This method introduces inherent variability between the individual surgeons tying the knot. However, by maintaining consistency within this study it is possible to compare the knot tightening forces between suture sizes.

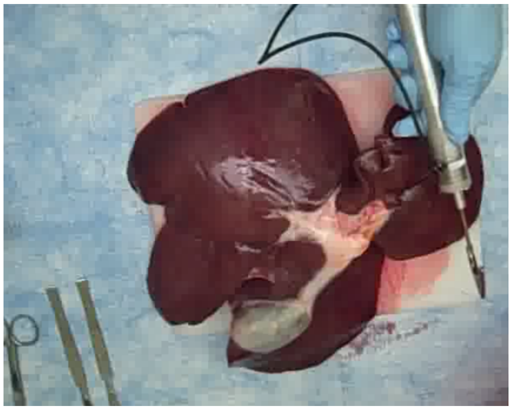

FIGURE 2. EVALUATION OF SUTURE KNOT TIGHTENING FORCE REQUIREMENTS.

The forces necessary to break the suture line were quantified, as this may allow the surgeon to quickly remove the needle from the line after completing the knot. A variety of suture sizes and types were evaluated including sizes 3-0 (2 metric) through 7-0 (0.5 metric) polypropylene (Surgilene, Davis & Geck), size 1 (4 metric) polybutestor (Novafil, Davis & Geck), size 4-0 chromic gut (Davis & Geck), and size 6-0 (0.7 metric) braided polyester (Polydek, Deknatel). Testing was carried out using a 250 Newton, uniaxial load cell (Part Number 4501018/B) mounted on a Qtest QT/10 (MTS Systems Corporation) tension testing machine. The suture needle was rigidly clamped as shown in Figure 3, which was itself mounted to the crosshead of the tension testing machine. The free end of the suture was then secured to the bottom frame of the tension testing machine using a looped knot. The crosshead was moved vertically at a rate of 0.1 meters per minute until breakage occurred. Displacement rates of 0.05 and 0.2 meters per minute were also tested but the dependence of the break force on displacement rate was found to be insignificant. This methodology allowed us to evaluate the suture break force regardless of the location of the failure.

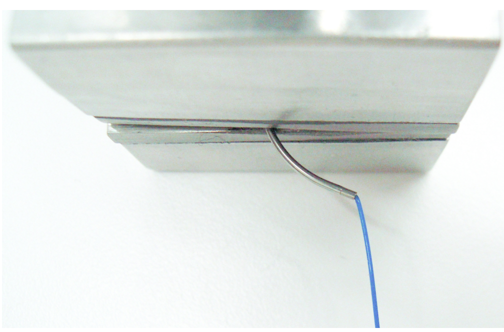

FIGURE 3. RIGIDLY MOUNTED SUTURE FOR MEASURING BREAK FORCE.

RESULTS AND DISCUSSION

As can be seen in Table 1, the greatest forces recorded during the abdominal force probing experiments were for manipulation of the kidney and liver tissues, which each demonstrated a measured load of approximately 3.5 Newtons. This result would be expected due to the rigidity of the kidney and the mass of the liver, each of which contribute to the increased force necessary to manipulate the tissues. The remaining abdominal tissues tested fell within a range of 1.3 Newtons to 2.5 Newtons.

TABLE 1. ABDOMINAL PROBING FORCE MEASUREMENTS.

Tissue	Force (N)
Liver	3.45
Gallbladder	1.32
Spleen	1.47
Stomach	2.53
Kidney	3.57
Bladder	1.53

Experimental data collected to evaluate the force requirements for suture tasks including tissue puncture and knot tightening is shown in Table 2, where *n* denotes the number of tests for each task. We can see that the tool force necessary for tissue puncture ranged from approximately 1.5 to 3.3 Newtons, while the force necessary for suture knot tightening ranged from 2.3 to 7.2 Newtons. These results demonstrate that there is a significant dependence on the suture size when considering the force requirement to tighten the suture knot. This corresponds well with the work of Kitagawa et al. in which the average tension applied to the suture by an attending surgeon was approximately 2 Newtons for size 4-0 polypropylene [7]. However, strong correlation between the two studies can not be predicted due to dependence on the individual surgeon.

TABLE 2. SUTURE TASK FORCE MEASUREMENTS.

Task	n	Force (N)	SD
Liver puncture	1	3.26	–
Gallbladder puncture	3	1.49	0.72
Size 4-0 knot tightening	3	2.28	0.10
Size 0 knot tightening	2	7.19	0.96

The forces necessary to achieve suture breakage are shown in Table 3, where the suture material tested was polypropylene (Surgilene, Davis & Geck) unless otherwise noted. When comparing the results with the literature for size 4-0 polypropylene, it was found that the force of approximately 6.75 Newtons presented here was much lower than the force of 13.76 Newtons presented by Trail et al. [11]. One possible explanation for this result is the location of breakage. In the experiment conducted by

Trail et al., the suture was secured by winding the line around two metal rods before taping it down. This would indicate that the suture failure must occur in the line. However for this study, the needle end of the suture was secured in a vice and it was observed that the majority of the failures occurred at the junction between the needle and the line. This would suggest that this junction is likely weaker than the tensile strength of the line. Since the focus of this study was to evaluate the surgical tool force requirements, and in particular for this experiment the force necessary to break the needle away from the rest of the suture, these results hold value. If it were determined that greater force was necessary to achieve a satisfactory knot, the surgeon would have the option of grasping the suture line in order to apply greater tension.

TABLE 3. SUTURE BREAK FORCE MEASUREMENTS.

Suture Size	n	Force (N)	SD
1 (Polybutester)	4	38.67	5.70
3-0	6	11.93	0.15
4-0	8	6.75	0.80
4-0 (Chromic Gut)	2	8.73	1.71
5-0	2	4.84	0.51
6-0	3	3.12	0.56
6-0 (Braided Polyester)	1	5.10	–
7-0	2	2.20	0.34

These results demonstrate that it will be necessary for the designers of novel surgical robotics to consider the specific applications that their tool is targeting when determining the limits of capability. Scarfogliero et al. presents a novel surgical robot designed for single-port laparoscopic surgery that is capable of producing 5 Newtons of force at the tool tip [12]. In a scenario such as this where increasing the force capacity of the tool may be size or cost prohibitive, it may be necessary to make use of other tools such as cutting instruments to achieve the forces that may be required for suturing tasks.

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