Experimental Analysis of Surgical Tool Force Requirements

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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

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surgical tools with the appropriate capabilities.

1 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 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 tool 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 [5–11]. Additionally, the abdominal organ tissues have been characterized in vitro with rectangular samples [12]. However, these studies have limited application to clinical applications and 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 needle away from the suture line, have 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 [13]. 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 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 intended [5]. The results of this study will help to define the force requirements for novel surgical tools for procedures involving suturing tasks and the manipulation of soft biological tissues.

2 Methods

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 a force probe to manipulate the tissue such as may be necessary during surgical intervention. The force was recorded as a 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 [13]. As can be seen in Fig. 1, the abdomen was open during testing, which would be similar to the conditions during surgery when the abdomen is inflated.

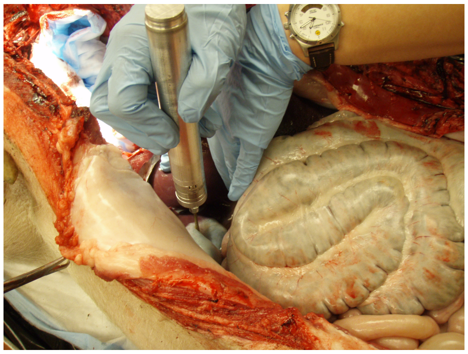

Fig. 1. Force measurements being taken in a porcine abdomen

The force probe used in this experiment consisted of a Nano25 six-axis transducer (ATI Industrial Automation) that was mounted between a handle and probing tip to provide an intuitive, portable interface for force measurement that could be used in the operating room (see Fig. 2).

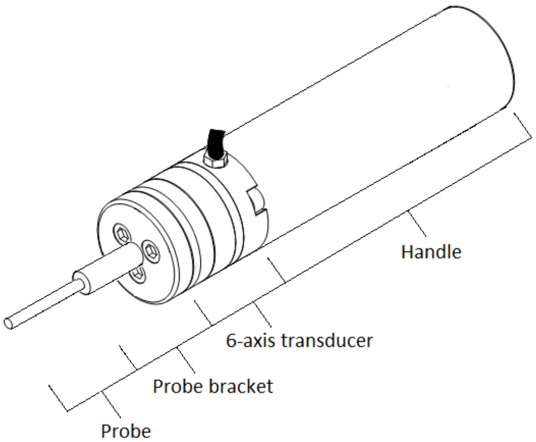

Fig. 2. Illustration of the mounted six-axis transducer

Results were also collected for common suturing tasks; tissue puncture and knot tightening, where high tool force requirements would be expected. The suture needle was attached to the force probe shown in Fig. 2 using an alligator clip and was passed through the tissue as would be done for a normal suturing procedure. For this experiment, both porcine liver and gallbladder tissues were examined. The peak magnitude of the force on the tool tip was recorded.

Table 1. Suture sizes and types evaluated for break force

U.S.P. Suture Size	Metric Size	Material	Product	Manufacturer
1	4	polybutester	Novafil	Davis & Geck
3-0	2	polypropylene	Surgilene	Davis & Geck
4-0	1.5	polypropylene	Surgilene	Davis & Geck
4-0	2	chromic gut	–	Davis & Geck
5-0	1	polypropylene	Surgilene	Davis & Geck
6-0	0.7	polypropylene	Surgilene	Davis & Geck
6-0	0.7	braided polyester	Polydek	Deknatel
7-0	0.5	polypropylene	Surgilene	Davis & Geck

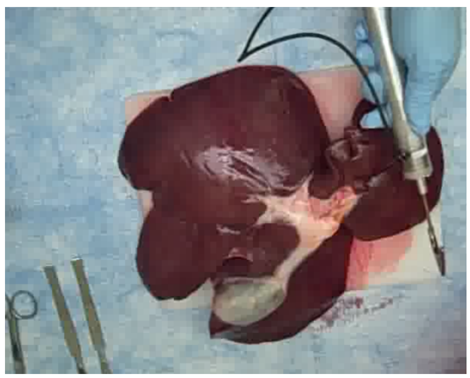

Fig. 3. Evaluation of suture knot tightening force requirements

Next, 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 tool tip force measured, until a satisfactory knot was formed, as shown in Fig. 3. 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.

Finally, the forces necessary to break the suture line were quantified using a variety of suture sizes and materials as shown in Table 1. The suture needle was rigidly clamped as shown in Fig. 4, which was itself mounted to the crosshead of a 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. Mounting the suture in this way allowed us to evaluate the suture break force regardless of the location of the failure. The break force was measured using a 250 Newton, uniaxial load cell (Part Number 4501018/B) mounted on a Qtest QT/10 (MTS Systems Corporation) tension testing machine. Additionally, the crosshead of the tension testing machine 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.

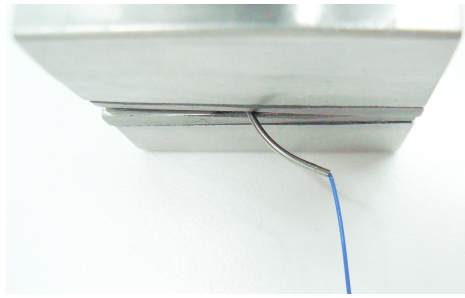

Fig. 4. Rigidly mounted suture for measuring break force

3 Results

As can be seen in Table 2, 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. The remaining abdominal tissues tested fell within a range of 1.3 Newtons to 2.5 Newtons.

Table 2. 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 the suturing tasks of tissue puncture and knot tightening is shown in Table 3, where n denotes the number of tests performed 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.

Table 3. 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 4, where the suture material tested was polypropylene (Surgilene, Davis & Geck) unless otherwise noted. It is apparent that the force requirement to tighten the suture knot is dependent on the suture size.

Table 4. 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

4 Discussion

The abdominal tissue manipulation results presented in Table 2 show that the greatest forces were measured for the kidney and liver tissues. 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. Although not directly comparable, tissue handling in terms of grasping force have been presented in the literature to have a mean value of 8.5 Newtons [14]. Thus, the forces recording during the abdominal organ manipulation experiment are expected to be within the safe range regarding the avoidance of tissue damage.

Suturing task forces, presented in Table 3, were found to range between 1.49 and 7.19 Newtons. The lowest force measured was for needle puncture of gallbladder tissue. However, a large standard deviation of 0.72 Newtons over three trials was found and was likely caused by variable tissue stiffness within the organ. The greatest force was measured for suture knot tightening using sutures of size 0. This result is expected due to the increase in bending stiffness of a suture line with a larger diameter. Finally, it was possible to compare the knot tightening force of size 4-0 suture with the literature. Kitagawa et al. measured the average tension applied to a suture by an attending surgeon as approximately 2 Newtons for size 4-0 polypropylene [9]. However, a definitive comparison between the two studies can not be made due to dependence on the individual surgeon performing the operation.

Lastly, the results for suture break force, seen in Table 4, show a range of 2.20 to 38.67 Newtons with a direct correlation with suture size. 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. [15]. 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 suture is likely to be held at the needle, the force necessary to break the needle away from the rest of the suture, regardless of location, is particularly relevant. Further, 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 knot tightening force.

5 Conclusions

The results presented in Section 3 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 [16]. 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 specialized tools such as cutting instruments to complete the specified task.

Achnowledgements

The authors acknowledge The Visible Heart Laboratory and the Medical Devices Center of the University of Minnesota for granting access to biological tissues and for use of their facilities and equipment, respectively.

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Table and Figure Captions