Proceeding of the IEEE
International Conference on Robotics and Biomimetics (ROBIO)
Shenzhen, China, December 2013

Development of Veress Needle Insertion Robotic System and Its Experimental Study for Force Acquisition in Soft Tissue

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***Abstract*— This paper presents a design and development of Veress Needle Insertion Force Sensing System, and a Veress Needle Insertion Robotic System for acquiring force data for soft tissue insertion. The study reports force data from veress needle insertions, measured to use in our Robot-Assisted Surgical System. The main goal of this work is to develop a virtual reality robotic surgical system which can provide accurate force feedback in laparoscopic surgery via a haptic device. The results from the needle insertion experiments presented, i.e., puncture force and friction force in fat, muscle, and the abdominal wall. These experiments can be applied to the study of all soft tissue and all needle types.**

***Keywords*—** Robotics, surgery, needle insertion.

I. INTRODUCTION

LAPAROSCOPIC SURGERY is one of Minimally Invasive Surgery (MIS). The laparoscopic instruments are introduced through ports which allow to access the body of patient. Patients for laparoscopic surgery have much shorter hospital stays, less pain, rapid recovery and early return to work compared to patients with open surgical procedures. However, the surgeon is not able to see directly and perceive into the patient unlike the open surgical procedures.

This project is financially supported by the Thailand National Research Grant (NRU) through Mahidol University, and is supported by the Center for Biomedical and Robotics Technology (BART LAB), Faculty of Engineering, Mahidol University for all the equipment. The authors would like to thank Prof. Chumpon Wilasrusmee, R.N., M.D. who is a Professor at the Department of Surgery, Faculty of Medicine, Ramathibodi Hospital, Mahidol University, Bangkok, Thailand, for the suggestions and comments. The authors would also like to thank all BART LAB members for all the help they have provided.

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In minimally invasive surgery, the surgeon performs many functions that are difficult and complex. Now, robotic assisted surgery or cooperative robot systems have been introduced to laparoscopic surgery which allows the surgeon to perform complicated surgery. The da Vinci Surgical system is robotic system that expands the surgeon's capability to operate in a less invasive way during minimally invasive surgery.

However, the lack of tactile feedback is one of the most significant drawbacks when using robotic assisted surgery and incorporate force feedback, giving the surgeon. The surgeon lack of ability to sense the environment while interacting with the robotics [1]. The ultimate goal of our research is to develop a collaboratively tele-operated robotic surgical system with a virtual reality-based robotic controlling system. The system can provide accurate force feedback in laparoscopic surgery using modified haptic devices that shown in the diagram in Figure 1. One of the most important components to be fulfilled in the system is the realistic force feedback that can be obtained from real forces applied by users on instruments during the surgery. Therefore, this paper presents our force acquisition system and its implementations.

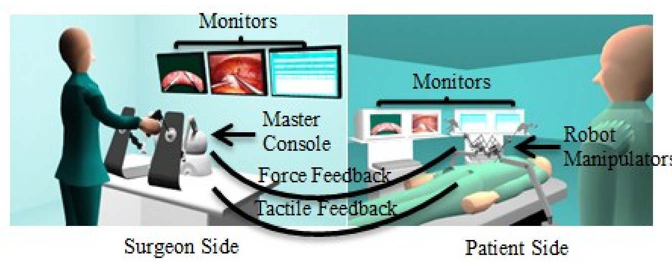

Fig. 1. Design of tele-surgical robotics system

A. Related Works and Their Analyses

A number of researchers have developed haptic virtual environments for surgical simulation, for procedures including [2] brachytherapy [3], lumbar puncture, epidural blocks, endoscopic surgeries [4], and laparoscopic surgeries.

Okamura *et al.* [5] study the forces involved in the needle penetration and withdrawal phases. A robotic controlled needle insertion system is measured for inserting a needle into bovine liver samples. Using a detailed modeling of the force components, the authors describe a methodology to separate the contributions of stiffness,

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friction and cutting forces, in order to derive a complete force model.

Meltsner *et al.* [6] study velocity effects in artificial phantom materials. They specifically investigated velocity effects during needle insertion into artificial phantom materials and presented results accordingly. The latter considered the range from 5 mm/s to 200 mm/s, whereas the others all used velocities in the range of 1 mm/s to 20 mm/s. The relation between shaft force density and velocity resembles the relation found for the total force vs. velocity by Crouch *et al.* [5]. Mahvash *et al.* [7] examine velocity effects during needle insertion into biological tissue. They considered velocities larger than 25 mm/s (up to 250 mm/s).

Veress needle is basic laparoscopic equipment in insufflator system. The surgeon will insert veress needle through the midline of patient's abdominal wall. We found that have injuries to the vessels and soft tissue by the veress needle reported in the literature resulted from midline punctures in the umbilical region [8, 9]. The risk of iatrogenic injury is minimized when the needle is not inserted through the midline [10]. During veress needle insertion, it is vital that the physician have detailed control of the needle insertion, position and velocity, since the area surrounding the target location can get attached and easily damaged. Complicating factors include tissue deformation before puncture, needle bending, and reduced tactile [2].

The prototype of this work was developed by modifying the needle insertion robotics system. The force sensor is mounted into an adapter for needle insertion to acquire force data at the human/tool interface [11]. The experiment included: The first purpose was to determine sampling rates (f_s) that are appropriate for soft tissue. The second purpose was to determine the constant velocity (v) that is appropriate for soft tissue. The third use results from appropriate sampling rate from the first experiment and results of appropriate velocity in the second experiment to set the experiment. The experiment was set up by testing needle insertion into three types of tissues of pig: fat, muscle, and abdominal wall, with a measuring surgical instrument.

II. Design and Development of Force Acquisition System for Veress Needle Insertion

A. Design on the Measuring Veress Needle Insertion

Veress needle is a common surgical instrument, used to make incisions on the patient's abdominal wall. The creation of a pneumoperitoneum is the first step of a laparoscopy. Most complications of laparoscopic surgery occur during its most critical step, namely access to the peritoneal cavity [12]. We design and develop two types of force acquisition system for veress needle insertion: handheld and needle insertion robotics system.

The handheld system is the system for manual experiment which is modified with an adapter to attach the force sensor shown in Figure 2a. And also for the robot experiment the adapter to mount force sensor into the needle insertion robotics system is shown in Figure 2b. Our system attaches to a force/toque sensor (ATI Industrial Automation) model-Nano 17 to measure the forces signal so the system is capable of measuring three components of force and three components of torque. The force data is simplified using a computer with a 16 bit NI PCI 6220 DAQ card (National Instruments). Veress needle has diameter of 2 mm and the length is 150 mm, and a beveled needle point for cutting through tissues of the pig. The tissues of pig scope in muscle, fat and abdominal wall without skin, tested at room temperature.

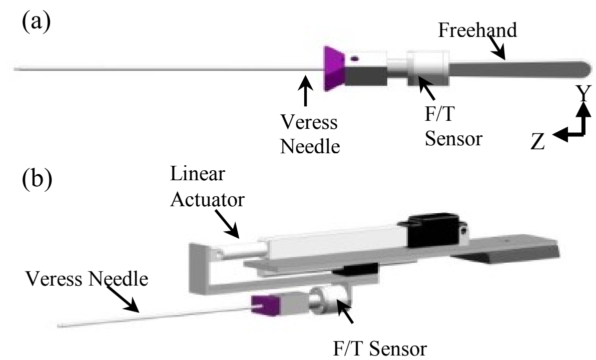

Fig. 2. (a) CAD design of our handheld veress needle insertion. (b) CAD design of our robotic needle insertion system.

B. Appropriate Sampling Rates (f_s) for Soft Tissue Experiments

The objective of this experiment was to determine sampling rates (f_s) that are appropriate with the kind of soft tissue. The experiments use all of the equipment discussed in the equipment topic. The setup in Figure 3 for these experiments, muscle (60 mm width, 100 mm height and 30 mm depth) and fat (60 mm width, 100 mm height and 15 mm depth) is used in order to obtain data that closely

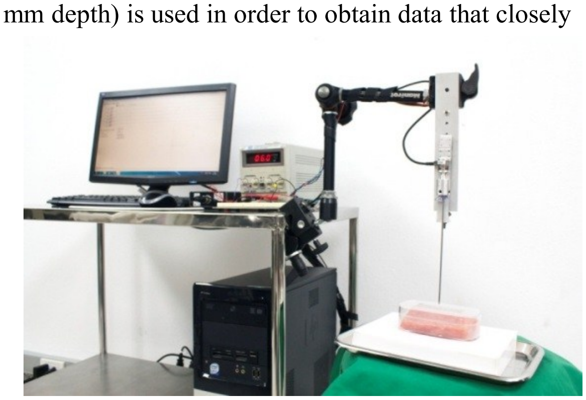

Fig. 3. Experiment set up with the needle insertion robotics system with F/T sensor, veress needle and a control computer for the data acquisition

corresponds to an intraoperative procedure. The data is sufficient to be used as examples in the analysis of the change that occurs. An experimental implementation of the proposed methodology was testing insertion of veress needles into soft tissue.

For the needle insertion robotics system, the adapter is mounted to the force sensor through the needle insertion robotics system which is developed in Figure 2b. Veress needle is fixed to a force sensor. Only the z-axis forces felt by a needle upon insertion are primarily along the needle's axis. For identification, the tip of the needle is placed 5 mm outside the tissue. The tissue is placed in a plastic container (60 mm width, 120 mm height and 35 mm depth, cut area of the center on the top and bottom of plastic container size 3x7 cm.).

In our experiments, the needle is moved towards the tissue until the linear actuator gives a stroke 70 mm. A veress needle was inserted at a constant velocity of 5 mm/s with approximately 21 cm^2 area over the surface of the tissue. This velocity is representative of the speed at which a doctor would insert a needle which is generally very small during an intervention [2]. Voltage data from the force sensor is recorded for three insertions at each of the following sampling rates: 250, 500, 750, 1000, 1250, 150, 1750, 2000, 2250, and 2500. Needle insertion data is logged for about 10 insertions at each of the sampling rates. Each insertion was done at a new location of the tissue in order to avoid the holes created during previous insertions.

C. *Appropriate Velocity (v) for Soft Tissue Experiments*

The objective of this experiment is to determine the constant velocity for the needle insertion robotics system that is close to the average velocity from a handheld procedure during an intervention. For our experiment the system setup is tested by inserting a veress needle into the soft tissue (using muscle 60-mm width, 100-mm height and 30 mm depth to represent the soft tissue). There are two types in this experiment achieved using different kinds of operators that are set up to compare a result: in both handheld and the needle insertion robotics system.

The experiments use all of the equipment discussed in the equipment section. For the handheld experiment the veress needle is modified to have an adapter to attach the force sensor shown in Figure 4. Only the z-axis was used for the forces felt by a needle upon insertion which are primarily along the needle's axis. For the needle insertion robotics system experiment, the setup is the same as the previous experiment "Appropriate Sampling Rates (f_s) for Soft Tissue Experiments".

For identification, the tip of the needle is placed 5 mm outside the tissue. The tissue is placed into a plastic container (60-mm width, 120-mm height and 35 mm depth). Voltage data from the force sensor is recorded at a rate obtained from the data analysis of the previous section.

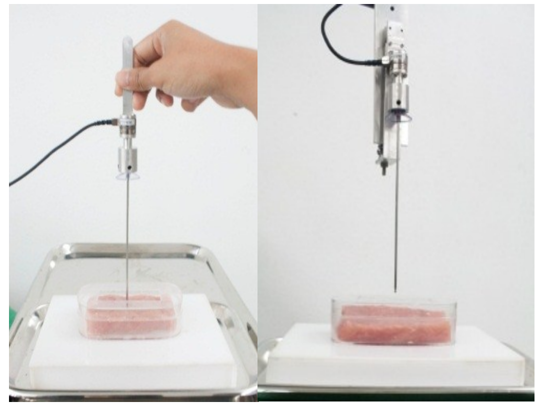

Fig. 4. Left: The handheld measuring surgical instrument.
Right: The measuring surgical instrument by needle insertion robotics system.

In our experiments, the needle is moved toward the tissue until the linear actuator gives a stroke 70 mm. The translational velocity of a needle insertion robotics system varies from 1 to 10 mm/s within approximately a 21 cm^2 area over the surface of the tissue. People insert the needle into soft tissue along the needle's axis until it goes through. Needle insertion data is logged for about 10 insertions for each soft tissue at a constant velocity.

D. *Soft Tissue Property Force*

Needle insertion consists of four phases: initial puncture, pre-puncture, puncture and post puncture. The force information from each phase is extracted to get important information about the individual forces acting on the needle. The objective of this experiment is to compare forces between different soft tissues. We use fat (60-mm width, 100-mm height and 30 mm depth), muscle (60-mm width, 100-mm height and 15 mm depth), and abdominal wall (without skin, 60-mm width, 100-mm height and 35 mm depth).

The experiments use all of the equipment and the same setup as the previous experiment "Appropriate Sampling Rates (f_s) for Soft Tissue Experiments". A veress needle is inserted at a constant velocity from data analysis in "Appropriate Velocity (v) for Soft Tissue (Muscle of Pig) Experiments" approximately a 21 cm^2 area over the surface of the tissue. Voltage data from the force sensor is recorded at a rate that is obtained from the data analysis in "Appropriate Sampling Rates (f_s) for Soft Tissue Experiments". The tip of the needle is placed 5 mm outside the tissue. The tissue is placed into a plastic container. In our experiments, the needle is moved toward the tissue until the linear actuator gives a stroke 70 mm. Needle insertion data is logged for about 10 insertions in each of the soft tissue.

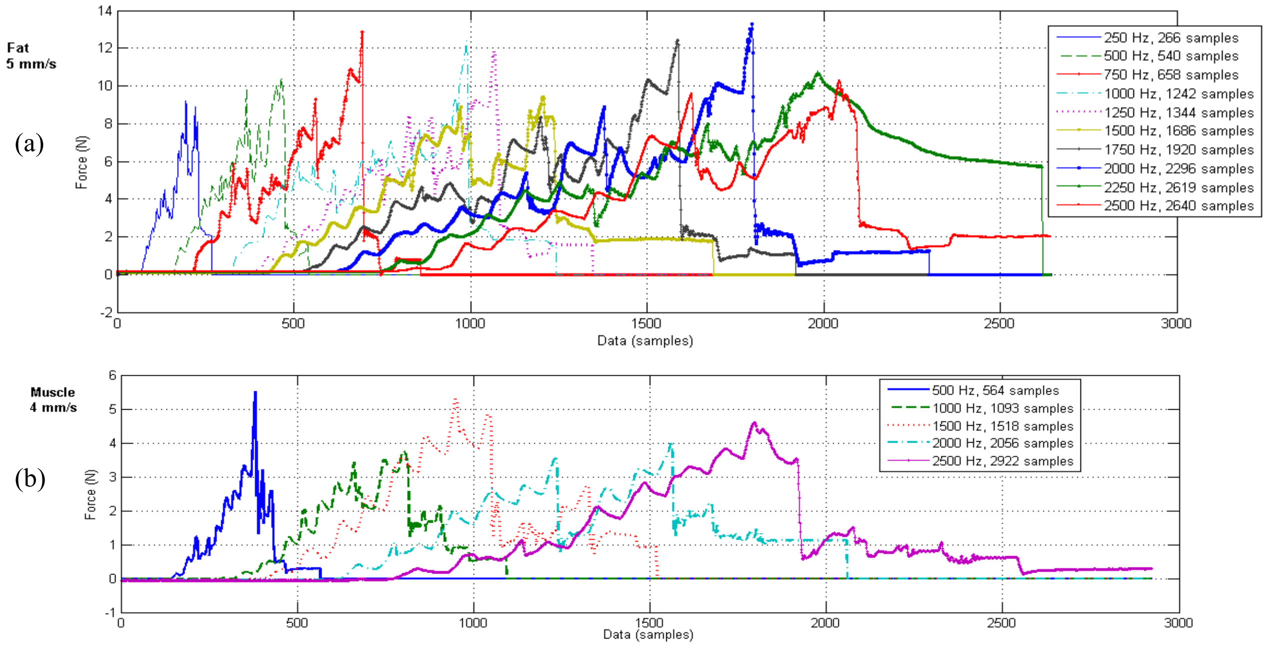

Fig. 5. Total veress needle insertion force (Newton) versus data (samples): (a) the result for the fat experiment (translation velocity for this experiment is set to 5 mm/s), 14 s. (b) the result for the muscle experiment (translation velocity for this experiment was set to 4 mm/s, 17.5 s.)

III. Experimental Results and Analysis

A. *Sampling Rates (f_s)*

The sampling frequency or sampling rate f_s is defined as the number of samples obtained in one second (samples per second), thus $f_s = \frac{1}{T}$. The results for the sampling rate experiments are shown in Figure 5. The graph represents the relationship between total veress needle insertion force (Newton) and data (samples) for all in fat experiments.

TABLE I
SUMMARY OF THE EXPERIMENTAL RESULTS OF THE TOTAL VERESS NEEDLE INSERTION

Sampling Rates (Hz.)	Data of Fat (Samples)	Data of Muscle (Samples)	Max. Force of Fat (N)	Max. Force of Muscle (N)
250	266	-	9.188012	-
500	540	564	10.43591	5.521898
750	858	-	12.87336	-
1000	1242	1093	12.39921	3.756536
1250	1344	-	11.87427	-
1500	1686	1518	9.407699	5.322030
1750	1920	-	12.41479	-
2000	2298	2056	13.29728	4.032320
2250	2619	-	10.74906	-
2500	2640	2922	10.27791	4.590612
Average			11.29175	4.644679
±SD			1.467457	0.773793

Comparison of voltage data from the force sensor is recorded at each of the following sampling rates: 250, 500, 750, 1000, 1250, 1500, 1750, 2000 and 2500 Hz. For this example data set, the needle is inserted at 5 mm/s. The graph in Figure 5b represents the relationship between total veress needle insertion force (Newton) and data (samples) for all in muscle experiments. Comparison voltage data from the force sensor is recorded at each of the following sampling rates: 500, 1000, 1500, 2250 and 2500 Hz. For this example data set, the needle is inserted at 4 mm/s. The average of the maximum force and data samples in fat and muscle are presented in Table I.

One set of results is shown in Figure 5. The experiment of needle insertion provides the linear measurement of the force. The zero position in Figure 5 denotes the tissue contact position and the peak of graph is the point at which tissue punctures occur. Table 1 summarizes the results of all of the veress needle insertions. The maximum force is 11.29175 ± 1.467457 N in fat and 4.644679 ± 0.773793 N in muscle. In Figure 5, we can see data clearly beginning sampling rate 1000 Hz. This rate, the force sensor is also recorded data not more than necessary.

B. *Velocity (v)*

The results for the appropriate velocity (v) experiments are shown in Figure 6. The graph in Figure 6 represents the relationship between total veress needle insertion forces (Newton) versus time (s). In each graph, comparison between the data for velocity from free hand and each constant velocity from needle insertion robotics system (constant velocity in the order of 1 to 10 mm/s). The blue dash line represents data from the handheld experiment and the red line represents data from a needle insertion robotics system. The time from the needle insertion robotics system at 5 mm/s is similar to the time from handheld.

The results for the needle insertion into soft tissue at each velocity are displayed in Table II which shows the comparison of period time and maximum force of muscle. We measure the time that the linear actuator takes to move forward from zero position to 70 mm position. This period is comprehensive for the needle insertion into soft tissue. The result show the maximum force required for puncturing is within 2.2275969 to 4.635742 N. and the average maximum force is 3.718225$\pm$ 0.635101 N.

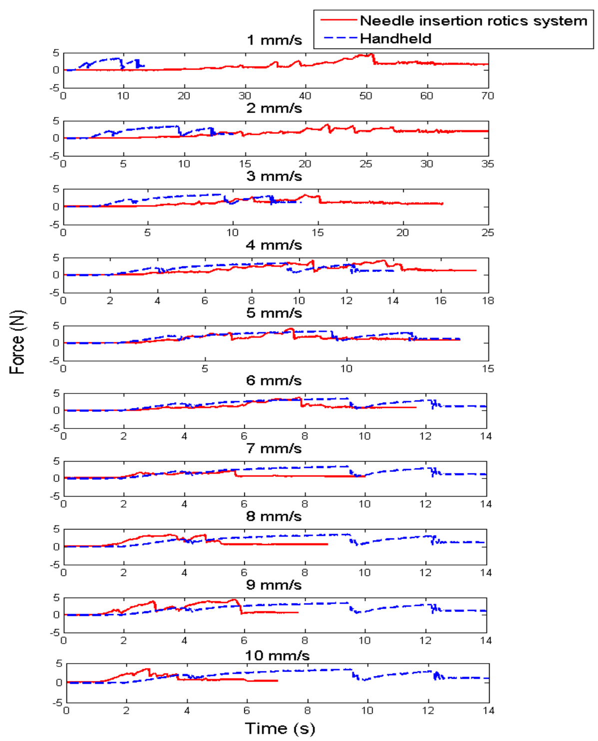

Fig. 6. Total veress needle insertion force (Newton) versus time (seconds), the translation velocity for this experiment was varied 1 to 10 mm/s

C. Soft Tissue Property Force

The graph in Figure 7. represents the relationship between total veress needle insertion forces (Newton) versus time (s). In each of the graphs a comparison of the major puncture events are shown for needle insertion in each of the tissues. For this example data set, we use the approximate constant velocity from the result of velocity that is 5 mm/s because it is more similar to the time from handheld. The constant velocity that is a representation of the speed at which a doctor would insert a needle is 4 mm/s [2]. For the voltage data, this is recorded from the force sensor. We use the approximate sampling rate from the result of sampling rate of 1000 Hz. We can see the changes that occur in each phase which is clear while the data obtained is not a lot.

The green dashed line represents the force data from needle insertion into fat, the dotted line represents force data of muscle and the red line represents force data from abdominal wall that is without skin. In addition, these graphs show the force data during an experimental needle insertion task broken into four phases: initial puncture, pre puncture, puncture and post puncture [2] as illustrated in Figure 7.

TABLE II
COMPARISON TIME AND SHOWN MAXIMUM FORCE AT EACH OF VELOCITY

Velocity (mm/s)	Average Period Time (s)	Maximum Force (N)
1	70	4.635742
2	35	3.925992
3	23.33	3.228569
4	17.5	4.127139
5	14	4.039433
6	11.67	3.779815
7	10	2.275969
8	8.75	3.477271
9	7.78	4.353242
10	7	3.631862
Handheld	14	3.425440
Average		3.718225
±SD		0.635101

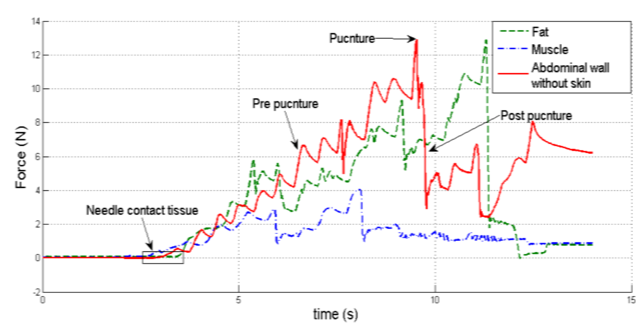

Fig. 7. Comparison of the total forces for insertion into fat, muscle, and abdominal. Insertion speed was 5 mm/s, sampling rate 1000 Hz.

Figure 8. illustrates the friction of the tissue that occurs, based on the force data, after the needle has been fully inserted because there is no tissue cutting involved. There is a difference between the friction for insertion at

fat, muscle and abdominal wall without skin. Table III shows the maximum cutting force and average friction force in each tissue. The maximum cutting force for fat, muscle, and abdominal wall is 12.897336 N, 4.039433 N, and 12.90211 N respectively and the friction force is 0.993568 ± 0.730102 N, 1.499921 ± 0.253097 N, and 4.808985± 0.845764 N respectively.

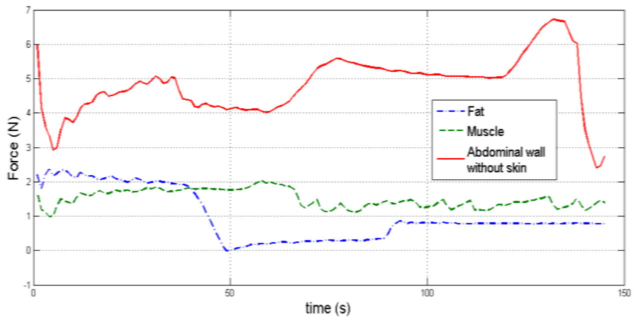

Fig. 8. Comparison of the friction forces for an insertion into fat, muscle, and abdominal. Insertion speed is 5 mm/s, sampling rate is 1000 Hz.

TABLE III
COMPARISON OF MAXIMUM CUTTING FORCES AND THE AVERAGE FRICTION FORCES FOR INSERTION INTO FAT, MUSCLE, AND ABDOMINAL WALL

Type of Tissue	Maximum Cutting Force (N)	Average Friction Force (N)	Standard Deviation (N)
Fat	12.897336	0.993568	0.730102
Muscle	4.039433	1.499921	0.253097
Abdominal wall	12.90211	4.808985	0.845764

IV. Conclusions and Future Work

The force acquisition of the veress needle, which is a basic laparoscopic equipment, insertion into soft tissue is reported. The prototype of this work is developed by modifying the needle insertion robotics system. The force sensor is mounted into an adapter for needle insertion to acquire force data at the handheld/tool and needle insertion robotics system/tool interface [11]. The experiment is set up by three topics. In the first experiment, the purpose is to determine sampling rates (f_s) that are appropriate for each kind of soft tissue. In the second experiment, the purpose is to determine constant velocity (v) that is appropriate with each kind of soft tissue. The third experiment uses results of appropriate sampling rates from the first experiment and results of appropriate velocity from the second experiment. The experiment is set up by testing the needle insertion of three types of tissues from pig: fat, muscle, and abdominal wall without skin, with a measuring surgical instrument. The results of the needle insertion show the different values of force in each tissue. While the actual results presented such as puncture force and fiction force are specific to fat, muscle and abdominal wall that without skin. The procedure for obtaining these results can be applied to the study of all soft tissue and all of needle type.

The force acquisition process is a part of virtual reality force feedback in the robotics surgery system. The main goal of our work is to develop a virtual reality robotics surgery system which can provide accurate force feedback in laparoscopic surgery with a haptic device. The future work includes the development of a virtual reality (VR) simulation for the insertion needle. And for more complicated surgical procedures, the force acquisition experiment can be developed by applying the concept of this work.

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