Needle Insertion Forces Studies for Optimal Surgical Modeling

Ka Wei Ng, Jin Quan Goh, Soo Leong Foo, Poh Hua Ting, and Teck Kheng Lee

***Abstract*—Needle insertion for minimally invasive surgery is a technique explored and studied in order to adhere to the strict regulatory requirement for medical device development. While the instruments and techniques determine the success of every surgical procedure, minimal attention was given to the medium, the interaction force for testing, the development tools and surgical techniques. In this paper, we present the interaction forces involve during the needle insertion into porcine back tissue and simulated flesh-like tissue, independently measured by a testing setup developed for this purpose. The experimental setup and test procedure provides an understanding on the mechanics of needle insertion, potentially aid the design improvement on surgical instrument. Investigation on the composition of the force components helps to define the bio-mechanical properties of back abdomen tissue upon insertion. These forces comprises of stiffness, friction and cutting force. These results estimate the true insertion depth of the needle in the tissue. Needle insertion forces were measured for gelatine analogues developed to model the consistency of the tissues in the lumbar region of the back. This study was the first step in developing a force feedback controlled surgical instrument for needle insertion which will be used in kidney surgical operation.**

***Index Terms*—Needle insertion, insertion forces, porcine tissue and gelatine.**

I. Introduction

Understanding biomechanical interaction between surgical needle and human tissues during needle insertion is crucial to the success of all invasive surgery [1]. Such studies are vital for the design of surgical instruments meant to assist surgeon in specific surgical procedures. DiMaio and Salcudean [2] studies shows that without an in depth understanding of the biomechanical properties of simulant or the availability of a realistic simulation model, the design of new medical tools may result in catastrophic consequences. Hiemenz *et al.* [3] studies shows that these understandings can prevent the accidental puncturing of vital organs, extensive tearing of skin tissues or inaccurate sampling during biopsy.

Many types of simulants with texture resembling that of human tissues have been made widely available but most remain a mock-up to the human tissues. Example includes the use of ballistic gelatine for firearms [4] and silicone for training simulation. The best replica closest to human tissue is the use of porcine tissue from specific portion of the animals. Such usages are usually costly and morally less acceptable compared to cheaper and widely available simulants.

The most common approach uses a portion of pork as the simulated subject. Alternative, the use of replacement jellifying agents is more convenient, readily available and received better acceptability over cadaver or animal testing. As gelatine is derived from animal collagen, it possessed similar properties and attributes to that of human tissues. Thus, gelatine is an appropriate tissue simulant for needle insertion force testing. In addition, the translucent, yet organic nature of the gelatine allows physical appreciation on the needle deflection during insertion. The formulated gelatine may be used to simulate layers of human flesh for replicating the needle penetration and extraction forces of the human flesh to reach an internal organ.

Needle insertion force affects the accuracy and eventually the duration of surgery [5]. A suitable and standard measurement procedure on the needle insertion force profile provides an accurate feasibility study on the usability of a needle guidance medical device.

This paper begins by describing the experimental setup, the procedure and the test samples. Next, the result and discussion of the experiments to characterize the various sources of force arising during needle insertion into porcine and simulated tissue (gelatine). Third, the discussion on the insertion force against the composition of the gelatin. Fourth, the impact of the temperature change of the gelatin and the multi-layered gelatin on the insertion force to simulate the invasive surgery. Finally, we provide conclusions and recommendations for future works.

II. Setup and Experimental Procedure

A. Experimental Setup

A bevel-tip needle, gauge 18, diameter of 1.12 mm and 15cm length is mounted to the digital force measurement gauge. The bevel tip is a cylinder cut through at an angle. The cone tip is a smooth cone with the peak at the center of the shaft, and the triangular tip contacts tissue with three sides of a tetrahedron (the tip at the center of the shaft). It is lowered down to touch the surface of the specimen. The needle is being inserted and readings are taken at every 0.1mm of needle entry. The specification of the motorized stand used is: Digitech, model: AFS-1000 and force gauge used for the test is: Digitech, model: DTG-2 with a capacity of 20N. Fig. 1 shows the experimental apparatus.

Manuscript received November 15, 2012; revised February 15, 2013. This work was supported in part by the Ministry of Education (MOE) Singapore under grant number MOE2010-IF-1-029.

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B. Experimental Procedure

In our penetration procedure, the needle is first positioned 1mm above the surface of the sample, driven down 80mm, then stopped and remained still in the prostate for 10 sec. The digital force gauge with a set of needles is attached on a linear stage, and driven vertically at a constant speed of 2.95mm/sec. Finally, the needle is withdrawn by 80mm. Data from the digital force gauge were recorded at a 50Hz sampling rate, together with the trigger signal of the linear stage controlled by a PC computer. The data is analyzed after the experiment. The penetration was performed five times, changing the puncture positions on the prostate surface to prevent the needle from going into the hole created by the previous penetration.

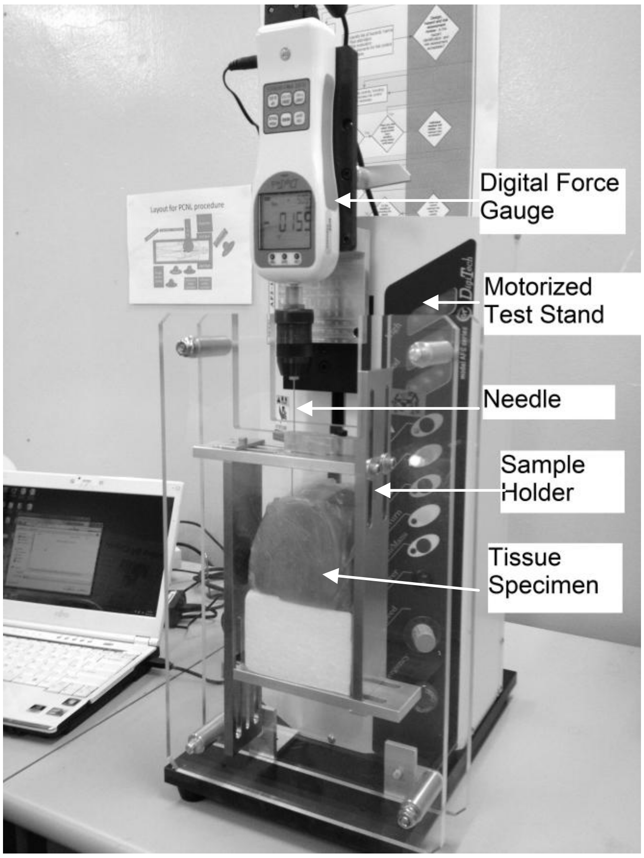

Fig. 1. Experimental setup.

C. Porcine Tissue Specimen

Two type of fresh porcine tissue (100 x 100mm) from the back abdomen are used as a closest replacement of human flesh near the kidney area. The fresh porcine tissue (1kg weight each) was prepared and frozen for 2 weeks until the experiment. After 3 days defrosting, it was used for the experiment. The temperature of the porcine specimen at the time of testing was 23.4C.

D. Preparation of Simulated Tissue Specimen

Formulated gelatine composition of 57gm is added to 1.9 liter of water. The gelatine's needle insertion result is compared to a piece of porcine specimen. As gelatine will liquefy when remain at room temperature for more than 30 minutes. Therefore, the duration of experiment is within 10 minutes. The temperature of the gelatine is kept at 4°C for the test.

III. Results and Discussion

A. Porcine Specimen Testing

Fig. 2 shows the insertion forces acting on the needle and the displacement of the needle tip penetrating into the porcine tissue (Sirloin). Each force data point was plotted from an average of five samples. The step line in the force plot is the trigger signal of the linear stage controller, and the position of the needle tip. The aim of the paper is to model the needle insertion force in the operation conditions.

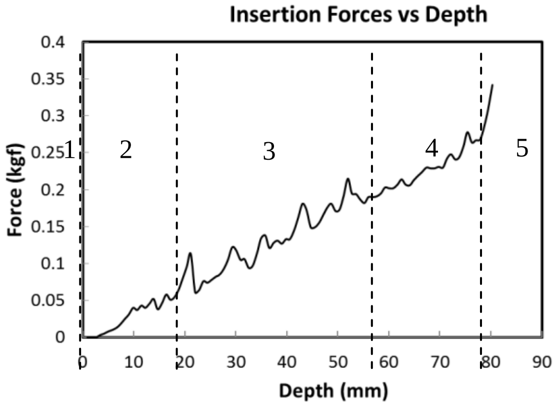

Fig. 2. Insertion force for porcine tissue, sirloin.

Interaction between the insertion force and porcine tissue exhibits non-linear properties. The formation of zigzagged force pattern in Fig. 2 implies that the existence of cutting force during the insertion. The cutting force refers to the force that the needle tip slicing through the tissue. We postulate that this force exists as a combination of cutting forces and the tissue stiffness at the tip of the needle. This is due to the needle tip compresses the tissue in front of the cuts. Ideally, the cutting forces will be constant, however from the experimental data in Fig. 2, it shows that the cutting force is inconsistent and it is unrelated to needle depth.

An example of the base forces and torques required to drive the needle along a simulated insertion trajectory. The trajectory proceeds as follows: (1) the needle tip makes contact with the tissue specimen, (2) the needle punctures the specimen surface and insertion continues along the y-axis, (3) insertion continues along the y-axis, with lateral base motion along the x-axis, (4) insertion continues along the y-axis only, and (5) end of insertion.

Segregating the sources of the force data into different components, allows accurate modeling of all the individual forces relevant to needle insertion. No design improvement of surgical instrument to date was made through explicit monitoring of such individual forces. Studying different components of the forces reveals critical information affecting the surgical procedure. Plotting force against needle tip position into porcine tissue reveals 2-staged puncturing, primary puncture followed by subsequent secondary punctures. This can be seen by the puncture event where a peak in force after a steady rise, followed by a sharp decrease (Fig. 2), identified by elevated forces and subsequent sudden drops in force. These subsequent variations in force are due to friction, cutting forces, and internal stiffness. It also reveals that the collisions of the needle tip with puncture of interior structures. Because the porcine tissue contains a substantial number of arteries and veins, the internal puncture events are evident in Fig. 2. Summation of the individual force components constitute the overall force data collected. Friction and cutting force are measured after occurrence of primary puncture while stiffness forces measure before needle insertion. Cutting force comprises of plastic deformation of the simulant and the tissue stiffness experienced at the tip of the needle. Internal stiffness of tissue affects the friction force.

The overall shape of the experimental results for using the porcine tissue (tenderloin) in Fig. 3 is similar to the data in Fig. 2, although the significant variations in porcine geometry and internal structure make a perfect match impossible. The different between these two different porcine samples are likely due to differences in small interior structures such blood vessels. The present of higher density of blood vessel in tenderloin tissue add additional peaks and stiffness forces to the data. We can assume that the needle remains completely straight as it travels through the tissue; in reality there are small deflections that may affect the measured force.

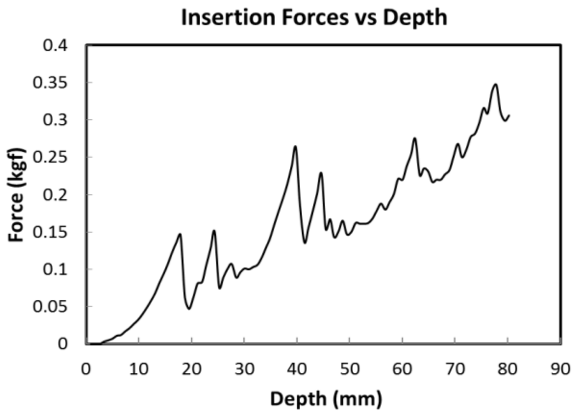

Fig. 3. Insertion force for porcine tissue, tenderloin.

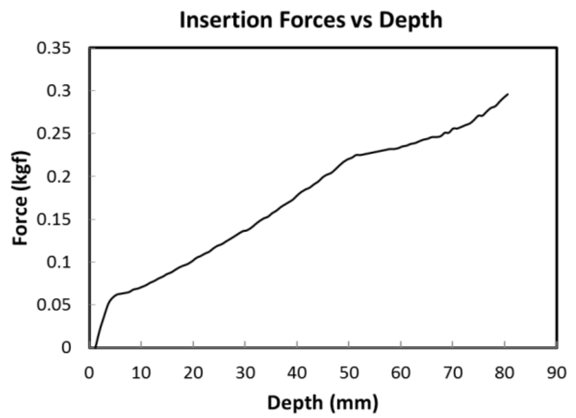

Fig. 4. Insertion force for gelatin.

Unlike the results shown in the porcine sample, the results for gelatine samples indicate that there is no cutting force. This implies that the forces insertion data segments are free from resistance of internal vessels. These internal resistances add an additional stiffness force that should not be taken into account when measuring the cutting force of the gelatine sample. Because of this factor, the measured cutting forces were not quite constant, but increased slightly with insertion depth. An example of cutting forces, separated from the stiffness and friction data, is shown in Fig. 4. The trials revealed a linear relationship between position and axial force as the needle is inserted. The slight distortion in the insertion force is observed when the depth is 50mm. This is most likely caused by a large amount of needle bending. A bevel-tip needle, unlike a symmetric-tip needle, will cut tissue at an angle. Since the needle cuts at an angle away from the direction of insertion, the needle may bend in the direction of the bevel. Past experiments have demonstrated the effect of tissue deformations due to rigid needle insertion [6].

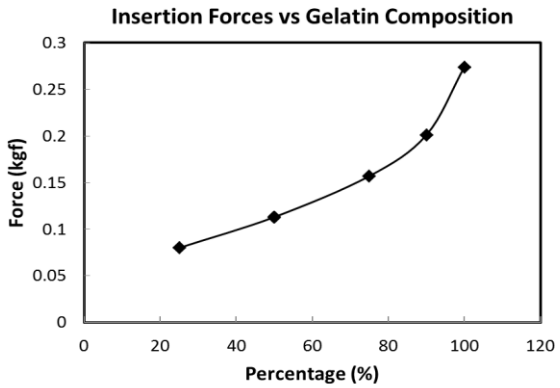

Fig. 5. Insertion force against the composition of the gelatine e.

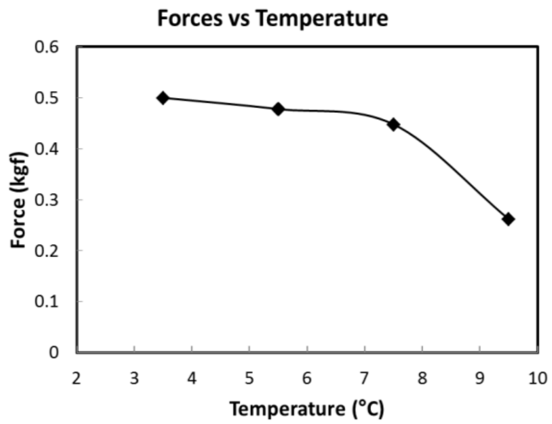

Fig. 6. Insertion force against the gelatine temperature.

B. *Insertion Force against the Composition Change*

The decrease of all the forces in Fig. 5 when the gelatine concentration is diluted using water is supposed to be caused by the changes in the viscosity. The decrease of the friction force was caused by the decrease of the dragging-up force of the gelatine edge facing to the needle, not by the decrease of the contact area on the needle surface to the gelatine , because it was observed that the gelatine surface did not move during the needle insertion. Fig. 5 also indicates that both insertion and withdrawal have the same pattern of force changes against the composition changes.

C. *Insertion Force against the Temperature Change*

Forces remain relatively stagnant before encountering steeper decrease when temperature starts to rise in Fig. 6. Temperature has an insignificant impact on the forces initially. As the temperature rise, the gelatin reduces in viscosity and rigidity of the mixture. Beyond the 8^{o}C mark, nearing to it melting point, the mixture becomes softer and provides less restriction friction and retention forces to affect the insertion and withdrawal forces.

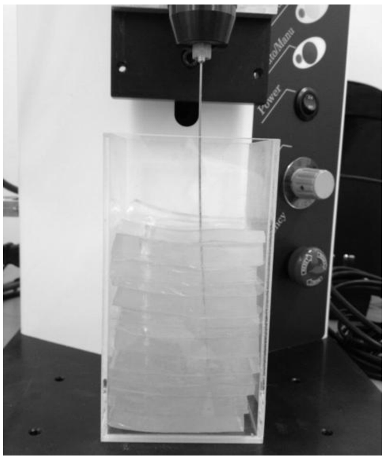

Fig. 7. Multi-layer gelatine e sample to simulate the porcine sample.

D. *Multi-Layered Simulated Gelatine*

The proposed multi-layered gelatine provides additional resistive forces between every individual layers, simulating veins and internal vessels. Multi-layered gelatine sample in Fig. 7 was formed by stacking multiple layers of both 5mm and 10mm thickness gelatine slabs with 0.1mm thick polymers sheets inserted in between each layers. Arrangement was placed in such a way to emulate the forces in Fig. 2. Bending of the needle was clearly visible through the translucent gelatine layered sample, not possible using porcine tissue where it is not transparent. A 5 degree bend was measured from the needle holding point to needle tip. Trajectory deviation in the insertion path was a normal occurrence. This is expected as the needle tends to follow the path with less resistance minimizing cutting force. This is unlike using homogenous sample where the observations are a straight insertion path with a linear increase of force with insertion.

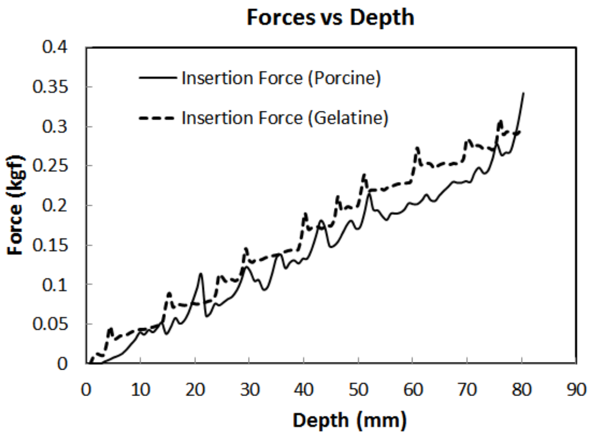

Fig. 8. Insertion force with simulated multi-layer gelatine compared with porcine sample.

Fig. 8 shows the insertion forces acting on the needle and the displacement of the needle tip penetrating into the porcine tissue (Sirloin) as compared to the simulated multi-layered gelatine. The result shows a close resemblance to the non-linear properties exhibited from the organic porcine sample. The simulated multi-layered gelatin also simulates the random cutting forces experienced from the needle tip. Magnitude and extent of the addition cutting force have been evidently replicated through the layering of the gelatine. When used for surgical training, this arrangement provides some form of kinesthetic or tactile feedback [7] which offers a more realistic training. The simulated setup provides a good approach on the design and usability of a needle guidance medical device.

IV. Conclusion

The tip force and the friction force on a needle during insertion into a porcine tissue were independently measured by a newly-developed test setup, and each force was related to the mechanical behavior of the porcine tissue. The linearity of the force during the insertion implies that the friction force was generated uniformly along the axis by the constant clamping force and the random spikes in insertion force. This is the result of cutting force penetrating the non-uniform veins and vessels. Additional experiments with the needles insertion for simulated tissue (gelatine) were performed as this jellifying agent is more convenient (transparent in nature which is more suitable for needle defection study), readily available and received better acceptability over cadaver or animal testing. The composition and temperature change are used to fine-tune the insertion force, while polymer sheets are inserted between the layers to replicate the cutting forces for the porcine. The needle insertion force for the simulated multi-layer gelatine resembles the actual porcine experiment and provides a good alternative medium for design or training of a needle guidance medical device.

References

[1] Y. Kobayashi, J. Okamoto, and M. G. Fujie, “Physical properties of the liver for needle insertion control,” in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, Sendai, Japan, 2004, pp. 2960-2966.

[2] S. P. DiMaio and S. E. Salcudean, “Needle insertion modeling and simulation,” in *Proc. IEEE Int. Conf. Robotics Automat.*, 2002, pp. 2098–2105.

[3] L. Hiemenz, D. Stredney, and P. Schmalbrock, “Development of the force feedback model for an epidural needle insertion simulator,” *Medicine Meets Virtual Reality*, vol. 6, pp. 272-277, 1998.

[4] D. S. Cronin and C. Falzon, “Dynamic Characterization and Simulation of Ballistic Gelatine,” in *Proc. SEM Annual Conference*, Albuquerque New Mexico USA, June 1-4, 2009.

[5] J. L. Westbrook, D. R. Uncles, B. T. Sitzman, and L. E. S. Carrie, “Comparison of the force required for dural puncture with different spinal needles and subsequent leakage of cerebrospinal fluid,” *Anesth. Analg.*, vol.79, pp.769-72, 1994.

[6] C. Simone and A. M. Okamura, “Haptic Modeling of Needle Insertion for Robot Assisted Percutaneous Therapy,” in *Proc. IEEE International Conference on Robotics and Automation*, pp. 2085-2091, 2002.

[7] E. Chen and B. Marcus, “Force feedback for surgical simulation,” in *Proc. the IEEE*, vol. 86, Mar. 1998, pp. 524 – 530.

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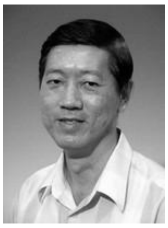

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